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# WORKSHOP ON TECHNOLOGY ISSUES OF SUPERCONDUCTING MAGLEV TRANSPORTATION SYSTEMS

James E. Wegrzyn (BNL) and David T. Shaw (NYSIS),
Workshop Co-Chairman

September 27, 1991

Prepared for presentation at Workshop on Technology Issues
of Superconducting Maglev Transportation Systems
New York State Energy Research and Development Authority
Brookhaven National Laboratory
and New York State Institute of Superconductivity
Upton, New York
May 23-24, 1991

DEPARTMENT OF APPLIED SCIENCE

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Special thanks are due to the speakers for their outstanding talks which led to valuable information exchanges, and to the session moderators whose efforts further raised the technical content of the workshop. They are:

| | |
|---|---|
| E. Forysth | Brookhaven National Laboratory |
| Y. Iwaza | Massachusetts Institute of Technology |
| S. Smith | Massachusetts Institute of Technology |
| G. Danby | Brookhaven National Laboratory |
| D. Thornton | Massachusetts Institute of Technology |
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# PREFACE

There exists a critical need in the United States to improve its ground transportation system. One suggested system that offers many advantages over the current transportation infrastructure is Maglev. Maglev represents the latest evolution in very high speed ground transportation, where vehicles are magnetically levitated, guided, and propelled over elevated guideways at speeds of 300 miles per hour. Maglev is not a new concept but is, however, receiving renewed interest. The objective of this workshop was to further promote these interests by bringing together a small group of specialists in Maglev technology to discuss Maglev research needs and to identify key research issues to the development of a successful Maglev system.

The workshop was attended by over fifty scientists and engineers with participation by the U.S. Department of Transportation/Federal Railroad Administration, the U.S. Army Corps of Engineers, the U.S. Department of Energy, the New York State Energy Research and Development Authority, and the New York State Thruway Authority. The attendees came from three national laboratories, fourteen private industrial firms and four universities.

New York State Lt. Governor, the Honorable Stan Lundine, delivered an inspiring luncheon address, in which he reaffirmed New York State's commitment to solve the State's future transportation needs. To this end, New York State is currently overseeing two studies that take a hard and close examination of very high speed ground transportation systems. These studies are being conducted by the New York State Thruway and Energy Authorities.

The workshop was organized into four sessions based on the following technical areas:

- Materials, Testing, and Shielding: High temperature versus low temperature superconductors, wire and cable fabrication, magnetic/ac fields interactions, high performance armor, and other special materials.

- Magnet Design and Cryogenic Systems: Magnet stability, shielding, weight reduction, on-board versus on-ground cryogenic systems, and advanced helium refrigeration.

- Propulsion and Levitation Systems: High efficiency induction versus synchronous motor, attractive versus repulsive system, loops versus continuous sheets, and on-board energy storage.

- System Control and Integration: Guideway and trackway configuration, system element, interfacing, and control, cost, and safety considerations.

Five to six panelists were invited to contribute to the session. Each panelist was given twenty minutes to present the key points of his/her position. These presentations were followed by a ten minute question and answer period. Each panelist was also requested to prepare a 3-5 page position paper on research needs and opportunities in his/her topical area. This manuscript is a collection of these papers.

J. Wegrzyn
D. Shaw

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**NEW YORK STATE MAGLEV RELATED PROGRAMS**

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## BACKGROUND

New York's transportation sector currently consumes over 41% of the total state energy use. Petroleum products are the source of approximately 95% of transportation energy use, and contribute the vast majority of carbon dioxide (CO), oxides of nitrogen (NOx) and hydrocarbon air pollution in the State. Projections indicate the total vehicle miles traveled will double in the next twenty-five years, thus further adding to air pollution, energy use and traffic congestion. Transportation is an integral ingredient in an industrialized economy. If our economy is to grow, so will our transportation needs. Unfortunately, our existing modes of transportation are reaching saturation.

Emerging technologies which potentially offer solutions to these problems include magnetically levitated (MAGLEV) and very high speed rail (VHSR) surface transportation. These electrically powered forms of transportation, operating at speeds up to 300 mph, are projected for use as an intercity transportation mode connecting cities within a range of 600 miles.

The New York State Energy Research and Development Authority (NYSERDA) Maglev related activities consist of;

1) Phase I: New York State Technical and Economic Maglev Evaluation

2) Phase II: High Speed Surface Transit Study

3) New York State Support for Federally Funded Maglev Research

## NEW YORK STATE MAGLEV PROGRAMS

1) Phase I: New York State Technical and Economic Maglev Evaluation

Although a final report has not yet been released the preliminary major findings of the Phase I study are as follows:

- o Technical Feasibility
  There are no insurmountable engineering or technological obstacles to developing and constructing a Maglev system in New York State. It was found that the NYS Thruway right-of-way could accommodate an average speed of 240 mph from New York City to Buffalo assuming banking (guideway and vehicle) of 24 degrees and crossing medians wherever necessary.

- Estimated Cost
  For the several Maglev configurations studied, the costs of the guideway structure and electrical system averaged $19 million (1990 dollars) per mile. Including the costs of the vehciles (approx. $9 million each), a current total system cost is estimated at $21.4 million per mile, or $10.6 billion for a 495-mile system extending from New York City to Buffalo.

- Estimated Ridership Levels
  Market demand was forecast for intrastate trips only. Based on a scenario of a 240-mile average speed, 20-minute headways and fares twice that of current intercity rail passenger fares, total intrastate ridership was estimated at abouve five million after ten years of operation. This is approximately four times the total number of current intrastate Amtrak trips on the corridor. This figure includes 2.1 million trips diverted from air and auto modes. A regional system incorporating other major Northeast, North Central and Canadian cities would increase demand considerably.

- Estimated Revenue/Amortization Levels
  Farebox revenue associated with the estimated 5.0 million intrastate trips would be approximately $340 million annually. This amount of revenue would cover estimated operating and maintenance costs ($157 million annually), but would not permit amortization of the capital costs of the system within a typical bonding period. These results are very preliminary and will be evaluated in more detail in future studies.

- Environmental/Energy Impacts
  Implementation of a intrastate Maglev system would reduce air pollution and fossil fuel energy usage attributed to current transportation modes. By the tenth year of operation, it is estimated that a Maglev system would reduce carbon monoxide emissions by 11,600 tons annually, hydrocarbons by 1,500 tons annually and result in 7.8 million gallons of fuel savings annuallly. These emission levels and fuel usage would equate for approximately 300 million car miles per year.

- Economic Development Potential
  The implementation of Maglev could have significant economic development benefits to the State. Only considering the actual construction of a Maglev system between New York City and Buffalo, almost 70,000 person-years of labor with $5.' billion in construction wages would be generated. In addition, more than 132,000 construction related person years of labor with more than $7.0 billion in construction related wages would be generated. Operating, maintenance and other related economic activity would generate over 1,000 new jobs, with total wages of approximately $79 million annually. Stations will generate significant residential and commercial development. Patterns of development will be changed; commuter sheds for the relatively affluent will be greatly extended. New York's research, manufacturing and financial services industries are well positioned to benefit from Maglev development.

## RECOMMENDATIONS

It should be noted that this study was conceptual in nature and limited in scope. Although it has provided a useful foundation in the preliminary findings above, its most important function was to identify the issues and future tasks required to comprehensively analyze the potential of a New York State Maglev system. The study recommendations are as follows:

- One of the competitive advantages of Maglev as a transportation mode is its ability to operate at speeds approaching 300 mph. The ability of the vehicles to sustain as high an operating speed as possible is a critical component to its implementation. Therefore, it is recommended that further, refined analysis of potential routes and their application as Maglev rights-of-way is a critical task and should be undertaken in future investigations.

- Market demand and ridership forecasts for an intercity Maglev system are critical in estimating the potential farebox revenue and its relation to total system costs and financing. A detailed market assessment including a forecast demand model, with appropriate origin and destination data as its foundation, should be pursued as soon as possible.

- Since the potential economic activities associated with the development, construction, operation and maintenance of a Maglev system are substantial, it is recommended that further economic analysis be conducted to make more precise estimates of these benefits. Detailed evaluation of these economic activities will be crucial in determining the overall benefits and advantages of a Maglev system as compared to major investments in other modes. Station development may also hold potential for providing non-farebox revenues to the system and should be analyzed.

- Due to the issues of real estate development, market demand, and integration with existing transportation systems, locations of stations becomes vitally important in Maglev development. It is recommended that this area be research thoroughly, including analysis of low-speed Maglev system development in suburban and urban areas.

- Additional research should be conduced in vehicle and guideway design and their interaction. Aspects of this work should include analysis of banking requirements and ride comfort criteria for vehicles and guideways. Other areas of research should include study of passive coil and flat plate guideway design including the null flux design, and high speed switching.

- Freight carrying capability requires further study. Maglev may offer a high speed and relatively low cost alternative to competing modes, in terms of operation and maintenace; however, a better understanding of potential freight markets is needed.

- Due to the importance of transportation safety, the on-going research into the effects of electro-magnetic fields (EMF) should be monitored.

All research into Maglev system design should address this issue with designs developed that can effectively shield the induced magnetic fields generated. However, it is imperative that the Federal Government set standards for EMF exposure. Further investigation of Maglev systems should also be used to develop system safety standards and operational standards which can address and minimize all potential safety situations that may be encountered, such as guideway misalignments, power failures, and levitation failures.

2) Phase II: High Speed Surface Transit Study

The overall objectives of the Phase II Project area: 1) to assess various competing technical approaches and their capabilities of meeting the future transportation needs of New York; 2) to quantify the benefits of VHSR/MAGLEV technology regarding potential energy and environmental impacts; 3) to assess corridor intrastate and regional development alternatives; 4) to perform market analysis and project ridership/freight potential; 5) to evaluate VHSR/MAGLEV economics and assess financing options; 6) to identify State industries with capabilities and interest in pursuing this technology; 7) to recommend an action plan for a New York State demonstration of high speed surface transportation technology.

Specific subject areas of Project which shall be addressed in the Project include:

- A comparison of commercially available VHSR/MAGLEV technologies;
- An assessment of current developmental efforts;
- A comparison of the cost of high speed surface transit system implementation vs. the cost of doing nothing;
- An identification of any technical obstacles to revenue service implementation;
- An assessment of the various corridors as a VHSR and/or MAGLEV right-of-way;
- Passenger and freight market assessment through the use of Forecast Demand Modeling;
- An assessment of reductions in petroleum consumption and energy costs in the transportation sector resulting from the implementation of VHSR/MAGLEV technology;
- An assessment of environmental effects;
- An assessment of the potential Statewide impacts of VHSR/MAGLEV upon economic development and urban revitalization;
- An assessment of financial feasibility, including capital costs, operating costs, projected revenue and availability of public and/or private funding.

3) New York State Support for Federally Funded Maglev Research

## GENERAL ELECTRIC CO.

Advanced Superconducting Magnet System

ERDA $ 50,000
FRA $350,000

## PARSONS BRINCKEROFF

Guideway Flexibility and Dynamic Forces

ERDA $ 32,000
FRA $168,339

Intermodal Equipment and Suspension

ERDA $ 35,000
FRA $134,026

## INTERMAGNETICS GENERAL

Superconducting Linear Motor

ERDA $ 35,000
FRA $147,000

Low-Cost U.S. Maglev Design (As Part of Consortium)

ERDA $ 20,000
FRA $450,000

## FEDERAL MAGLEV PROGRAM

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NATIONAL MAGLEV INITIATIVE

The Federal Railroad Administration (FRA), the U.S. Army Corps of Engineers (USACE), and the Department of Energy (DOE) are working in partnership with the private sector and state governments to assess the role of maglev in the Nation's transportation future. The goal of this cooperative effort, the National Maglev Initiative (NMI), is the improvement of intercity transportation in the 21st Century through the development and implementation of commercially viable, advanced maglev systems.

Day-to-day activities are managed by the NMI program office, directed by Robert L. Krick, FRA Deputy Associate Administrator for Technology Development. Stuart Kissinger of USACE is the Deputy Director; Patrick Sutton of DOE is the Assistant Director; and Dr. John Harding of FRA is the Chief Scientist. The program office is located in the DOT headquarters building in Washington, DC, with support from the Volpe National Transportation Systems Center, the USACE Huntsville Division, and the Argonne National Laboratory.

## NATIONAL MAGLEV INITIATIVE
## NMI Goal and Objectives

- Goal - improve intercity transportation in the 21st century through development and implementation of a viable, advanced maglev system
  - Define maglev's role in U.S. transportation system
  - Promote application of maglev technology in the U.S.
  - Promote development of a U.S. maglev industry
- Objectives
  - Assess viability in the U.S.
  - Determine development approach
  - Stimulate private sector development

# NATIONAL MAGLEV INITIATIVE
## Background Activities

- 1969-1975 FRA Maglev Research

- 1988 Railway Safety Improvement Act

- 1989
  - Senator Moynihan sponsors maglev feasibility study
  - FRA maglev safety task force
  - OMB technology cross-cutting review
  - Interagency coordinating committee established

- 1990
  - National Maglev Initiate
  - Forum Washington, DC
  - FRA feasibility study
  - CE preliminary implementation plan
  - Workshop Chicago, IL
  - RFP for technology assessments

- 1991
  - Technology assessment proposals accepted (28)
  - RFP for system concept definition (FEB)
  - Proposals for SCD (Apr)
  - Technology assessment awards (Jul)
  - System concept definition awards (Aug)

## Current NMI Activities

- September 1992 Decision Point
  - Economic and market studies
  - Technology assessments
  - System concept definition
  - Intermodal considerations
  - Safety issues
  - Use of highway and railroad rights-of-way
  - Implementation issues
  - System/Programmatic analyses

# NATIONAL MAGLEV INITIATIVE
## Funding

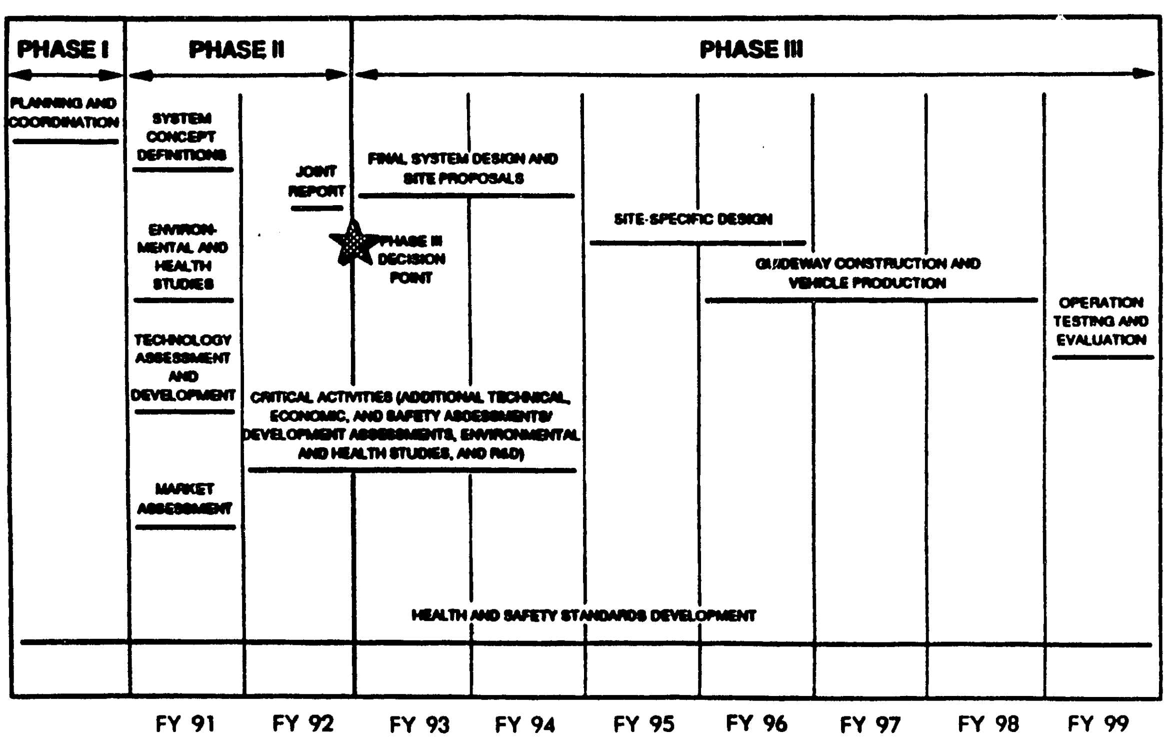
The Administration requested research and development funds for 1991 to assess the role of maglev in the future U.S. transportation system. Congress appropriated $10.2 million for NMI activities. These funds are being used to identify maglev concepts for use in the United States and to assess the technical and economic feasibility of the systems.

The Administration's request for maglev research in 1992 is for $19.5 million to continue the assessment of maglev initiated in 1991 and advance the concepts into simulation and testing.

## Maglev Decision Process

A key milestone will occur in the fall of 1992 (see the figure below) when the NMI will produce findings on the potential role of maglev in future U.S. transportation and recommendations for Federal decisions on further maglev development. They will be based on detailed evaluations of maglev system concepts as developed in several industry proposals. The industry will have the benefit of more than 28 maglev technology assessment projects to provide insights into opportunities for improving performance, and for reducing costs and risks of sub-systems and components. Besides the concepts and technology assessment work, other important elements of the initiative include safety evaluation, right-of-way considerations, and intermodal connections.

## MAGLEV DECISION PROCESS



# NATIONAL MAGLEV INITIATE
## Technology Assessment

- Broad agency announcement process

- Major system components/technologies
  - Propulsion
  - Levitation
  - Cryogenics
  - Superconductivity
  - Magnetic fields
  - Power
  - Alignment
  - Guideway
  - Control/Sensing
  - High speed operations

- Twenty eight, 8-18 months

## System Concept Definition

- Private sector define conceptual maglev systems

- Multiple teams

- Define feasibility, capabilities, risk, etc.

- Criteria:
  - Effectiveness
  - Understanding of technical factors
  - Completeness

# NATIONAL MAGLEV INITIATIVE
## Market & Economic Analysis

- Alternative economic scenarios
  - Growth in travel demand
- Ridership & revenue estimates
  - Specific zone pairs
  - Sensitive to speed, etc.
- Cost estimates
  - Sensitive to system design
- Public benefits, impact, "spin-off"
- Apply to "generic" systems in 1991
  - Status quo incremental investment
  - Generic maglev
  - Generic high speed rail
- Apply to system concepts in 1992

## Baseline Research and Development

- Parallel with mainstream R&D
- Get smart for technical support and decision making
- Fill in R&D gaps
- Reduce risk in critical areas
- Reduce costs in high payoff areas
- Promote innovation and technology transfer
- Demonstrate federal commitment
- Develop a U.S. maglev industry capability

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## INTRODUCTION

"Linear Motor Car - Maglev" technology offers an unique solution to world-wide problems. One of them, which is currently re-considered in the U.S., is the application to a high speed ground transportation system, which is safe, fast, free of noise and vibration, free of pollution, and also economical to operate.

The U.S. Department of Transportation's Federal Railroad Administration, along with the Department of Energy and the U.S. Army Corps of Engineers, are in the process of re-assessing the U.S. research and development need of Maglev technology. But if the U.S. decides to boost a major Maglev program in the near future, what would be the purpose and the strategy for it?

As the U.S. re-enters the race for Maglev technology in cooperation of or in competition with foreign nations, it will be necessary to study a wide range of Maglev and Maglev-related activities which have taken place outside the United States in the past twenty years. This is due to the fact that the U.S. lacks a crucial ingredient -- actual Maglev hardware, in order to conduct some forms of "reverse engineering."

From a broad perspective, two problems can be identified which could inhibit the current and the future U.S. Maglev effort. They are the problem of "perception," and the problem of "information."

(1) Problem of Perception:

The word "Maglev" (shorten from Magnetic Levitation): was invented by Dr. Howard Coffey in 1968. But it referred to the technology applied only to a form of high speed ground transportation, utilizing strong magnetic forces for levitation, guidance, and propulsion.

Long before the term "Maglev" was invented, the term "Linear Motor" had been used in Europe since 1841 (in combination with other technical terms to specify the nature of the technology), as the development and applications of the linear motor technology began.

England is the first nation in the world that applied this "Linear Motor" technology and commercialized the magnetically levitated linear motor transportation system via electromagnets.

France, in 1969, introduced "Aerotran Suburban (S44)" that was levitated by air-pressure but was propelled by an LIM. This technology was later transferred to the U.S., and was demonstrated at the TTC in Colorado, and attained a maximum speed of 275 km/h.

Italy, 1969, also tested a system similar to that which France had developed (air-pressure levitation, LIM propulsion), called "IAP2," and attained a maximum speed of 250 km/h.

Germany tested and developed various types of "Linear Motor" transportation systems, utilizing EMS, AC, EDS, RW, SLIM, DLIM, ICLSM, ACLSM technologies, and is about to commercialize the final version of Transrapid system. Simultaneously, a much lower cost people mover type "Liner Motor" system, called "M-Bahn," was developed.

Canada developed both low-speed and high-speed "Linear Motor" transportation systems. Only the low-speed system, called "Sky-Train," survived, and the high-speed Electro-Dynamic superconducting "Linear Motor" transportation system program was terminated by its government.

In Japan, the word "Maglev" was never officially used until recent to describe the same technology referred by Dr. Howard Coffey. It was always referred to (and it is still referred to) "Linear Motor Car" or simply "Linear." Here are some of the examples of transportation systems developed in Japan, which are called "Linear Motor Car."

a. The Ministry of Transport (MOT) developed EML-50, utilizing EMS/LIM methods. This system was developed in the 70's to significantly reduce the noise and vibration common to the most conventional railroad systems. The 160 m test track was built in Kanagawa Prefecture, to prove the technical feasibility. It was planned to be a relatively low-speed (120 km/h) urban transportation system. But it was never commercialized in Japan because the government could not find an appropriate location to commercialize the technology.

b. Japan Air Line (JAL) began the research and development of HSST (High Speed Surface Transportation System) in 1974. It went through the five stages of development. It basically utilizes EMS/LIM methods. It is also a relatively low-speed (up to 200 km/h) urban transportation system. It is already commercialized in Japan, and JAL is planning to market the technology at various locations around the world.

c. Osaka Municipal Transportation Authority decided to deploy a subway system, utilizing SLIM technology to take advantages of Linear Motor Car technology. Tokyo Metropolitan Transportation Authority also decided to deploy the same system, utilizing the same technology. Both systems were developed under the Japan's Subway Association, with the government and the industry support since 1985.

d. Japan National Railway (currently Japan Railway - JR) began the research and development of Linear Motor Car in 1962, went through the eight stages of development in terms of the demonstrated systems, utilizing superconducting magnets for guidance, levitation and propulsion. Currently, further advancing R&D efforts are still being undertaken at the Miyazaki Test Center, at the same time the new test track is being constructed in Yamanashi Prefecture.

Unlike the expression "Maglev," the expression "Linear Motor Car" gives a wide variety of meanings. There are two basic categories for "Linear Motor." One category is "Linear Motor" as in LDM (Linear DC Motor), LIM (Linear Induction Motor), and LSM (Linear Synchronous Motor). Another category is "Linear Actuator" as in LES (Linear Electric Solenoid), LOA (Linear Oscillatory Actuator), and VCM (Voice Coil Motor).

The U. S. should be planning its present and future Maglev program with this type of broad and integrated perspectives.

(2) Problem of Information:

Technical and non-technical information exchange on Maglev technology among the nations is still not at a satisfactory level, due to various political and cultural differences, especially between the U.S. and Japan. The U.S. also has an additional disadvantage in educating bi- or multi-lingual scientists and engineers.

Much of the information gathering activities engaged by and required for U.S. scientists and engineers are inadequate. This sometimes leads to a misunderstanding that non-U.S. systems, such as Japanese organizations, are "closed" or "secretive." And sometime, the way that U.S. scientists and engineers conduct information gathering outside the U.S. cause confusion and mistrust among the Maglev community.

The father of the Japanese superconducting Linear Motor Car technology, Mr. Yoshihiro Kyotani, always associated "Linear Motor Car" with the Electro-Dynamic SCM guidance, levitation and propulsion system; however, Mr. Kyotani's diversified evolutionary approaches to develop the final ED superconducting Linear Motor Car system have given Japan a wide variety of optional "Linear Motor Car" technology, applicable to many other commercial opportunities which are described later in this paper.

From the foregoing historical background, it is clear that we in the U.S. should not restrict the scope of Maglev development merely to a high-speed ground transportation.

The U.S. needs to develop the kind of strategy that will allow multi-directional simultaneous development of "Linear Motor Car - Maglev" technology. The U.S. should also be aware of the fact that not only the industrialized Western nations but also various NICs (Newly Industrialized Countries), such as Taiwan, Indonesia, India, Korea, China, etc., are showing extremely strong interest in the technology, and they are developing their own R&D and commercial programs on "Linear Motor Car - Maglev" technology.

The Maglev-related information obtained from throughout outside the U.S. could significantly assist in the development of its own Maglev program, and could in fact open up various commercial opportunities domestically and internationally.

(3) Why IMTC?

1. Limited access to foreign technology and information: There is a vast amount of information available on Maglev and Maglev-related fields

outside the U.S. Little, however, is written in English, and systematically organized under an unified system. Most of the information can be obtained if a proper channel is found (See the view graph #1 as an example of the Maglev Technical Information Exchange Program that could be re-established between the U.S. and Japan). In many cases, the gate is open, but few U.S. scientists and engineers try to investigate how to open such a gate.

2. Lack of international database on who is doing what, where, why and how: This fundamental information often become difficult to obtain, because there is no such system specifically designed for this purpose and also because there are still very few people who recognize the importance of such a system.

3. Lack of knowledge about various applications of Maglev technology: It is important to realize the fact that there are various technologies based on Maglev, some of which are already commercialized and some of which are still in the process of further research and development. Depending on such applied technologies listed below, some of them would not be appropriate for certain nations depending on its already established conditions. It is important to assess each applied technology and determine the usefulness of the technology based on each country's unique position. The U.S. should remember that many original patents to develop these applied technologies came from the U.S., but there is insufficient understanding about these technologies which symbolize the unlimited potential of Maglev technology.

a. Tube Vehicle System (TVS): Linear Motor Car - Maglev system operating in an evacuated tube for passenger and freight services.

b. Total Transportation System (TTS): Linear Motor Car - Maglev system operating in an evacuated tube, which is also used to transmit energy by superconducting wires and digitalized data by fiber optic cables.

c. Super Cargo System (SCS): Linear Motor Car - Maglev system operating in a small evacuated tube, designed specifically for light weight freight transport within metropolitan cities.

d. Space Vehicle Launcher (HIMES-LMATO): Linear Motor Car - Maglev system which assists the take-off of space vehicles up to 500 Km/h.

e. Tube-Style Launcher: U-shape underground tube Linear Motor Car - Maglev system, in which a rocket attains a maximum velocity for take-off.

f. Micro-Gravity Research Capsule: Underground tube Linear Motor Car - Maglev system to simulate micro-gravity conditions at lower cost.

g. EQUOS (ECOS-LIM Car): Automobile version of Linear Motor Car Maglev system, which also runs at a maximum speed of 500 km/h.

h. SEMP Ship/Submarine: Direct application of Linear Motor Car Maglev system for ships and submarines, propelled by hydro-magneto electrodynamic forces.

i. etc.

(For the detail description of the above mentioned Maglev-applied technology, please contact IMTC.)

(4) IMTC's Background and Current Status:

The idea was proposed by the author in the Fall of 1990, and gained the initial support from Mr. Ross Olander and Dr. Gopal Samavedam of Foster-Miller Inc., in Waltham, Massachusetts. The idea for IMTC was, at that time, created due to the unique approach that Foster-Miller Inc. was implementing to engage in the U.S. Federal Maglev Initiative program. The Foster-Miller's approach required a thorough global-scale understanding about the already existing Maglev technologies. IMTC has smoothened the process of obtaining information, particularly about the Japanese superconducting Maglev technology which later played a key role in determining the technical basis for the Foster-Miller's Maglev system concept.

It was February of 1991 when the IMTC was officially recognized by the management of Foster-Miller, Inc. At this point, Foster-Miller envisioned to broaden the IMTC's role to serve not only the company's technical interest but also to serve the entire U.S. and the other Maglev communities.

IMTC, however, is still in the early stage of conceptual development. IMTC is in the process of establishing a charter and inviting membership enrollment from interested parties. IMTC is currently receiving various direct and indirect input from individuals and organizations from several countries.

(5) IMTC's Tentative Charter: Based on the limited experience and discussions with limited individuals and organizations, IMTC's current tentative charter is as follows.

1. IMTC plans to promote world-wide Maglev technologies and applications in multi-lingual environment.

2. IMTC plans to create an international forum of Maglev technologies (in the form of newsletters, conferences), to exchange ideas and opportunities, on regular basis.

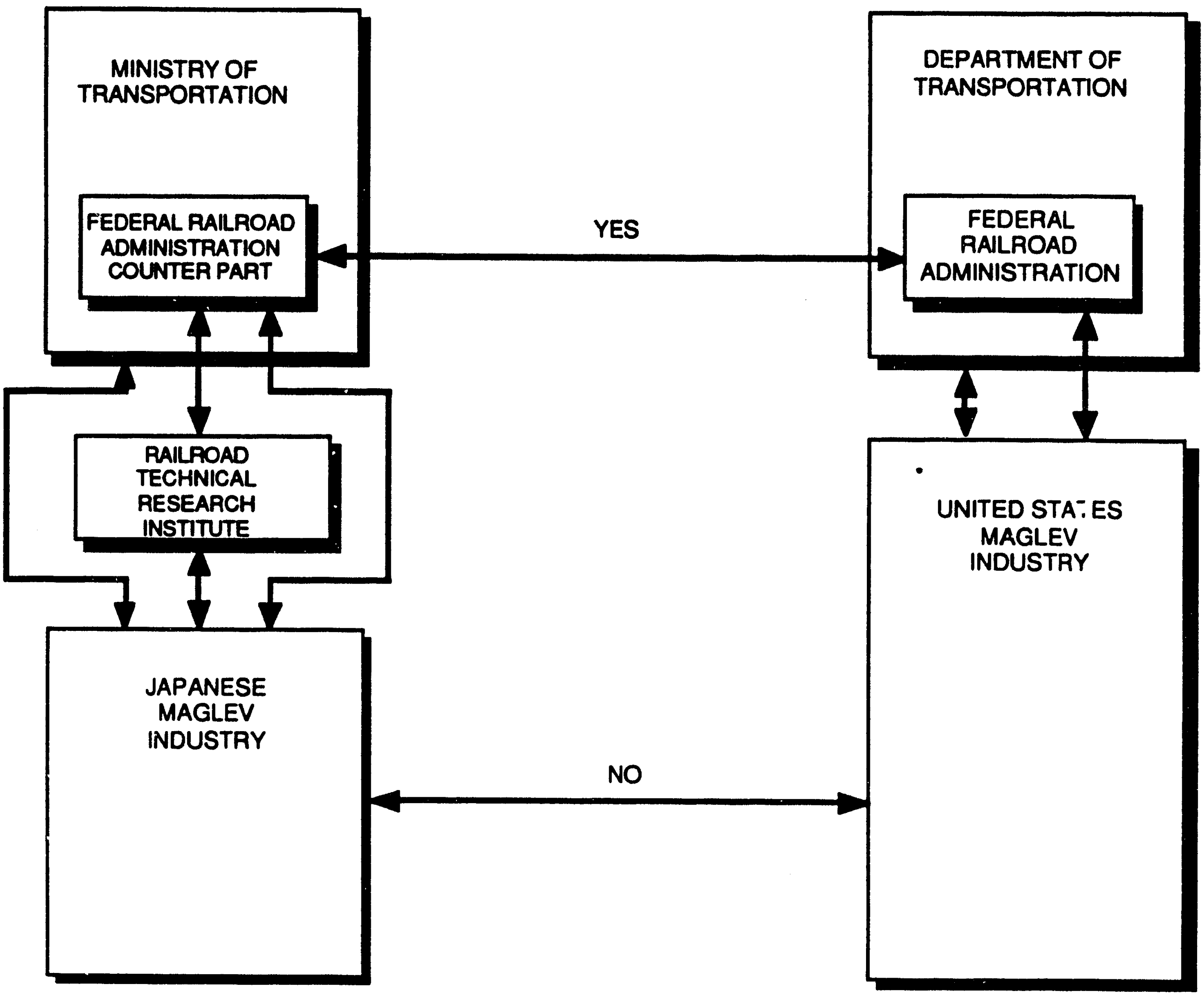
3. IMTC plans to identify R&D, government contract, and commercial opportunities to utilize Maglev technologies throughout the world.

(6) Concluding Remarks:

1. The present momentum on Maglev in the U.S. and abroad and the future potential growth will necessitate an international ground that can be provided by IMTC.

2. The U.S. scientists and engineers can benefit from IMTC by being properly informed about means and channels of communication and protocol observed in foreign nations.

3. IMTC is in the process of finalizing its charter and IMTC will solicit comments and any direct or indirect involvement of all interested parties.




Viewgraph #1. Maglev Technical Information Exchange Program

# INTERMETALLIC SUPERCONDUCTORS - THE STATE OF DEVELOPMENT IN 1991

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## I. STATEMENT OF PROBLEM

The commercial fabrication of intermetallic superconductors has reached a high degree of maturity in the past thirty years. The only significant, commercial requirement for superconducting wire is the construction of magnetic resonance imaging (MRI) devices for medical diagnosis. In addition to this demand there are one-time projects such as a high energy particle accelerators which often need considerable quantities of superconducting material over the few years of construction. R&D projects also provide a fluctuating market for superconducting materials, in the past the projects have included power apparatus such as generators, motors, energy storage and transmission cables, and magnets for experimental fusion reactors. Superconducting magnetically levitated trains have undergone full scale trials in Japan and Germany. This is by no means a comprehensive list of all the possible applications. Virtually all the devices requiring a magnetic field to be produced by superconducting windings have used NbTi wire, but a few experimental $Nb_3Sn$ high field magnets have been constructed. In the case of these materials commercial vendors can provide a high degree of quality assurance on such characteristics as critical current, coupling effects and mechanical tolerances.

## II. BACKGROUND

### Niobium Titanium

The high ductility and resistance to work hardening has made niobium titanium the preferred superconductor for virtually all applications requiring the winding of coils. The length of superconductor in these coils depends on the type of application: persistent mode operation requires no joints and continuous lengths of 15 to 30 km can be supplied for such applications. Powered operation such as accelerator magnets can usually accept minimum continuous lengths as short as 3 km.

The current carrying ability of NbTi has improved continuously since the discovery of this alloy. In the past five years or so the driving impetus for improvement has been the requirements of the magnets for the Superconducting Super Collider (SSC). This improvement is shown in Figure 1. Typical current densities available as a function of field with temperature as a parameter as shown in Figure 2. Tantalum has been used as a barrier to prevent the formation of copper-titanium.

Designers are usually faced with a compromise between cost and the number and size of filaments. The ramping rate, field aberration, losses and magnetization effects must be judged against the cost of conductor with many filaments. Typically, dc solenoids such as used in MRI apparatus possess from one to about a hundred filaments, the conductor for the SSC dipole magnet has a few thousand filaments each about 6 microns in diameter. Experimental wires have been developed for the SSC with about 20,000 filaments of 2.5 micron diameter. Not only is the cost driven up by extra processing but such conductors usually exhibit lower critical current densities and have a propensity to break. Conductors have been made for 50 to 60 Hz sine wave excitation, in order to minimize losses very fine niobium titanium filaments are embedded in a copper-nickel matrix. The filament diameter is between 0.1 to 0.2 microns and nearly a million filaments have been embedded in a wire only 0.3 mm in diameter.

Niobium-Tin

The A15 compound niobium-tin is the "best" commercially available superconductor, in that it has the highest critical values of temperature, field and current. However, it is considerably more brittle than niobium titanium; strains greater than 0.1% are likely to produce degradation of performance and for this reason it has seen little use in applications requiring "mass production" of magnets. Various fabrication methods have evolved to make multifilamentary $Nb_3Sn$ on a commercial scale. Filament diameters in the micron range are available. The limit on tolerable strain has led to fabrication methods for wound coils involving "wind and react" techniques. This requires electrical insulation which can withstand high temperatures when the wire is reacted. Several high field dipoles and solenoids (10 T or greater) have been made and one large Tokamak coil was made with niobium-tin, both "react and wind" and "wind and react" methods have been tried. Small percentages of other metals are often used in the preparation of $Nb_3Sn$. Titanium is often used, the field and current densities at 4.2 K are shown in Figure 3.

Niobium-tin tape was developed with low-loss characteristics of 60 Hz for a prototype power transmission cable. The first requirement for low losses is high critical current density; values of about 6000 $A/mm^2$ at 4.2 K are implied based on loss measurements. In order to provide strength and stabilization the niobium-tin tape is sandwiched between copper and stainless steel, as shown in Figure 4.

III. DISCUSSION

In Figure 5 a comparison of intermetallic superconductors and a form of ceramic superconductor is shown in the plane of current density vs field, it was prepared by the Intermagnetics General Corporation. For magnetic field applications below about 8 to 10 T NbTi has been the overwhelming choice of designers. This is mainly because the mechanical characteristics, such as ductility, lend themselves to relatively easy magnet assembly. The cost of NbTi is between $50 to $100 per lb, depending on the number of filaments, whereas $Nb_3Sn$ is in the vicinity of $300 per lb. The higher cost of $Nb_3Sn$ may be justified on occasions if operation at higher temperature can save on cooling cost or if higher fields save on the capital costs of a device, such as a reduction in the circumference of an accelerator.

Numerous intermetallic superconductors using binary and ternary compounds have been used in experimental superconducting devices; $Nb_3(Al, Ge)$, $Nb_3Ga$, NbN and many others have been evaluated for applications, generally the production costs have restricted wide-scale use.

The ceramic superconductors face at least two difficulties for use in magnets: relatively low current densities and extreme brittleness. It is this latter factor which has seen $Nb_3Sn$ excluded from most magnet applications, although it has been commercially available for over two decades. The low current density of present-day ceramic superconductors may be improved by further R&D. If this proves to be the case the focus will shift to the cost of commercially fabricated conductors. It is impossible to speculate about cost at the present time as virtually no multifilamentary designs have been produced using the new high $T_c$ material.

## IV. ACKNOWLEDGMENT

Much of the quantitative data presented in this paper was supplied by the Intermagnetics General Corporation, Inc. Helpful discussions were held with Meyer Garber of Brookhaven.

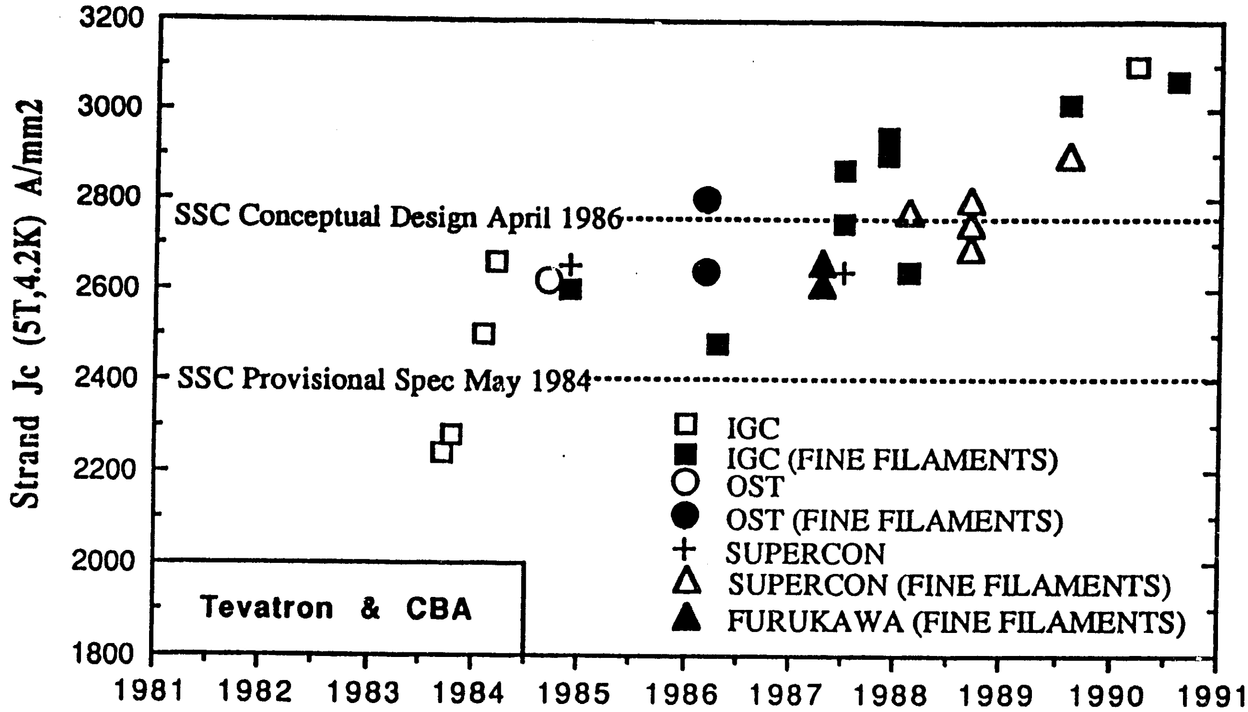


Figure 1. Improvement in $J_c$ of NbTi in the past six years.

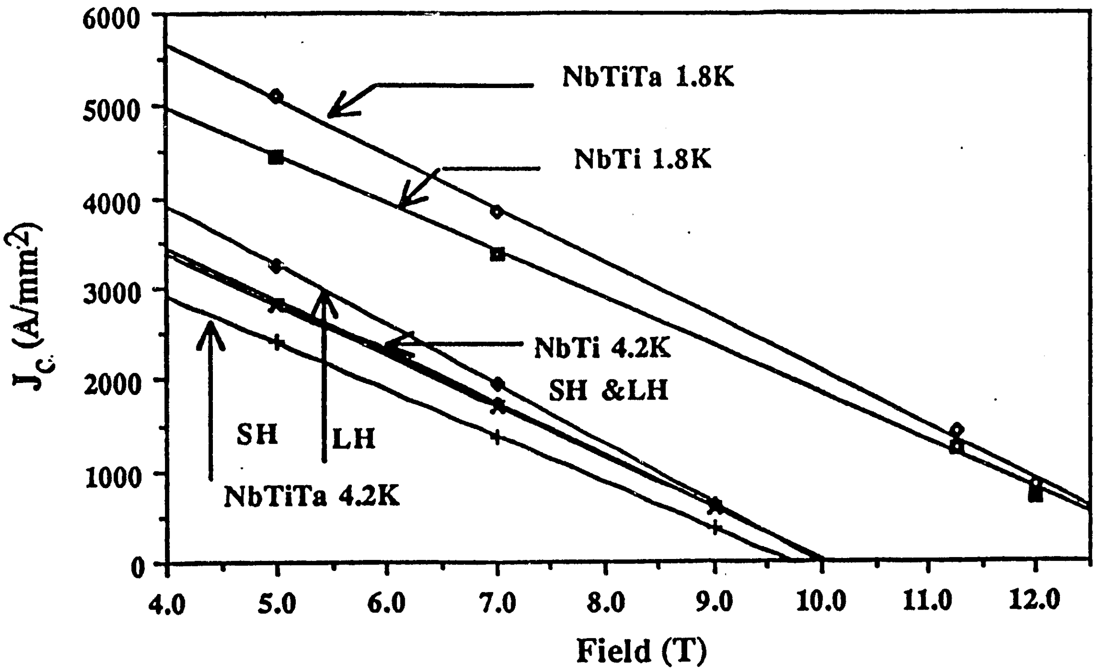


Figure 2. $J_c$ versus field at 1.8 and 4.2 K for Nb TiTa and NbTi. SH - short heat treatment; LH - long heat treatment.

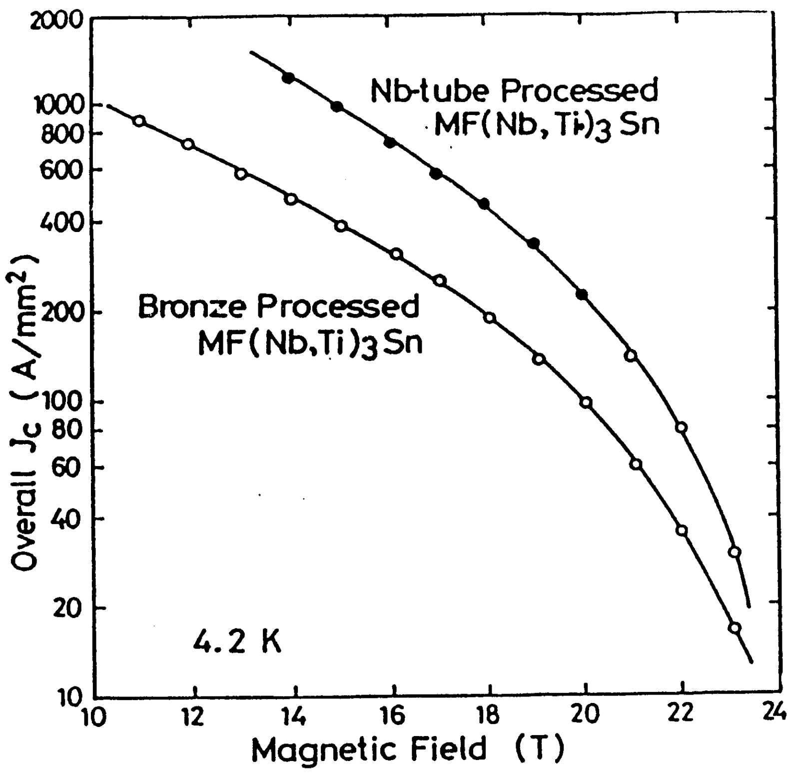


Figure 3. Overall $J_c$ (without Cu) vs magnetic field curves at 4.2 K for the Nb-tube processed and the bronze processed $(Nb, Ti)_3Sn$ multifilamentary conductors.

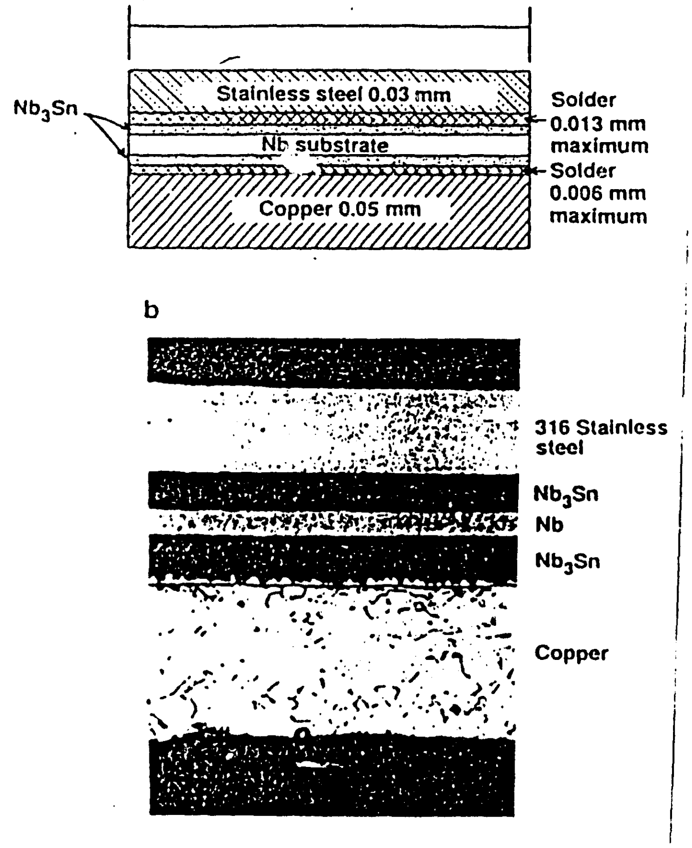


Figure 4. Cross section of the superconducting tape. (a) The tape design in diagrammatic form; $Nb_3Sn$ is made at the surfaces of a Nb inner substrate. Cladding layers of stainless steel and Cu are then soldered to the $Nb_3Sn$ surface. (b) Cross section has been etched to permit differentiation of the components.

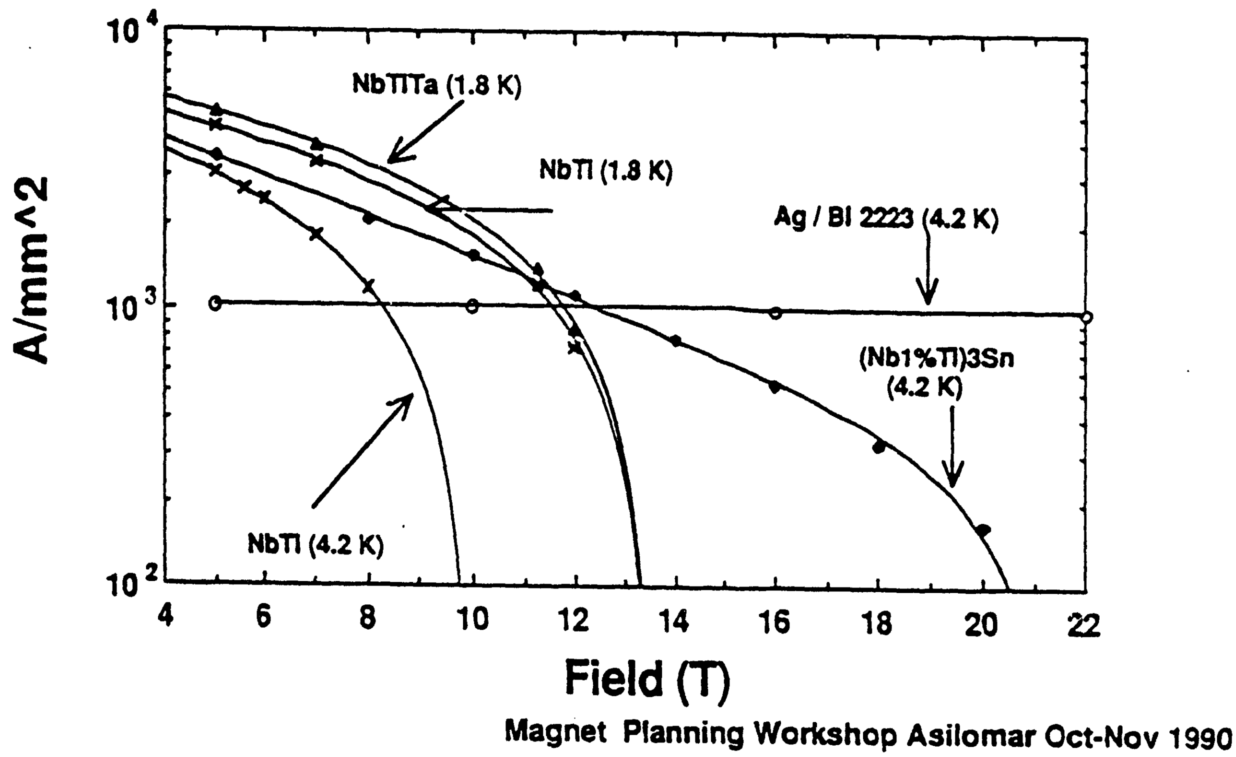


Figure 5

Assessment by IGC of various materials at 1.8 K and 4.2 K.

# DESIGN OF ADVANCED STRAY FIELD SHIELDING FOR MAGLEV

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## I. STATEMENT OF PROBLEM

Because the magnetic fields in maglev are large enough to levitate significant loads, the potential exists for large stray fields. Consideration for human exposure, to protect persons wearing pacemakers for example, and the need to protect electronics will result in guidelines for the maximum allowable field levels within different regions of a maglev system. Attenuating stray fields from maglev sources such as levitation and guidance magnets to allowable levels will add to the cost, weight, and power requirements of a maglev system.

There are essentially two methods for shielding magnetic fields; passive shielding and active shielding. Passive shielding of dc magnetic fields has traditionally involved high permeability materials which provide a preferred low reluctance path for the magnetic fields. A more recent passive shielding method utilizes superconducting material which totally excludes magnetic fields if the magnitudes are below the material dependent critical level $H_{C1}$. Above $H_{C1}$, shielding is dependent on the flux pinning characteristics of the superconductor material. Active shielding systems utilize strategically placed coils to create canceling magnetic fields; thus reducing the field levels in the appropriate regions of space.

## II. BACKGROUND

Passive shielding with high permeability materials is straightforward, simple, and inherently more reliable than active shielding. However, attenuating stray fields to low levels on the order of several gauss requires large amounts of traditionally heavy ferromagnetic material. To reduce the weight penalty associated with passive shielding, the shielding material can be minimized through an analysis based on a specific maglev design and the shielding material might be integrated into the car structurally[1]. Another passive alternative is to build the shielding into the magnet design. Using a ferromagnetic yoke, self-shielded superconducting magnet designs eliminate the need for large surface area shielding of a passenger compartment, but incur the shielding weight penalty at the magnet level[2]. Superconducting magnets have traditionally used air cores because the magnetic fields typically exceed the saturation levels of ferromagnetic materials.

The recent development of superconducting materials with transition temperatures above that of liquid nitrogen offers another alternative for passive magnetic shielding. Below a material dependent critical magnetic field level, these superconductors act as perfect shields, completely excluding the magnetic field from all but a surface layer approximately 0.5 μm thick[3]. If the magnetic fields are low enough, superconducting thin films are an effective, potentially lightweight passive shielding system. Shielding experiments with YBaCuO superconductors have shown $H_{C1}$ critical field levels which range from 17 to 23 gauss at 77K and 40 to 105 gauss near 4K[4],[5],[6]. These critical levels are still too small as flux densities at the passenger compartment floor level for several superconducting maglev systems have been shown to be on the order of 200 to 400 guass[1].

At magnetic fields above $H_{C1}$, complete shielding breaks down and the magnetic field penetrates into the superconductor. The depth of penetration is dependent on flux pinning, flux lines surrounded by small vortices of current which are trapped by material defects. The flux pinning characteristics are heavily dependent on the superconductor microstructure and are not necessarily stable. The pinned flux lines can creep into the superconductor interior resulting in the loss of all shielding effects. For high $T_c$ superconductor shielding above the critical level, the flux pinning must be stable. A recent paper on the shielding properties of YBaCuO cylinders using this flux pinning effect has shown the possibility for shielding fields of 10 kilogauss at 77K and predicts shielding of up to 80 kilogauss[7].

Of course, superconducting shields will require cooling power. Furthermore, it is not clear whether fabrication techniques for thin films with a high-oriented microstructure will scale to the large surface areas required for maglev shielding while maintaining the proper superconducting shielding characteristics.

Low temperature superconducting shielding using Nb-Ti is technically feasible today: coating large areas is not difficult and the critical field level where shielding breaks down is on the order of 500 gauss. The additional power requirements for maintaining 4.2K would most likely be prohibitive, however.

Active Shielding

Active shielding systems, which create canceling magnetic fields, have been developed extensively to shield magnetic resonance imaging (MRI) magnets[8],[9],[10]. These systems use superconducting compensation coils as an integral part of the MRI magnets to eliminate the need for flux-containing iron yoke structures which weigh on the order of tons. In a maglev application, typical field requirements may require large currents and result in losses which are impractical for standard room-temperature conductors. If superconducting coils are used, then once again, additional cryogenics must be added for the shielding system. For superconducting compensation coils, there is a trade-off between placing the coils near the levitation magnet cryogenics and placing them further away so that smaller compensation currents are required[1]. Finally, adequate shielding may not be possible without a complicated system of compensation coils.

Areas for Investigation

While there are still a wide range of alternative design concepts for electrodynamic maglev systems and the shielding requirements are poorly defined, the most useful information will be general in nature. Shielding characteristic curves, weight-power-cost trade-offs, and design methodologies for optimal shielding will be useful in development of a complete maglev system which meets the stray field requirements with minimum weight and power.

As specific maglev systems are proposed, electromagnetic analysis tools can be used to evaluate the magnetic field levels as a function of space and thus determine the field attenuation necessary to meet the allowable field levels. These tools can also be used to optimize, verify, and compare the various shielding designs. The following paragraphs outline areas where investigation is required. Some are design specific while others, such as development of superconducting thin film technology, are general in nature.

Two approaches exist for passive shielding with high permeability materials. The shielding can be incorporated into the magnet design such that the magnet is self-shielding, which implies a heavy magnet with a ferromagnetic yoke, or the shielding can be located away from the source and adjacent to the region which is to be shielded, such as the passenger compartment of a maglev vehicle. In this case, the shielding material should be as far away from the magnet as possible to minimize both the required field attenuation and the attractive force between the magnet and shielding material. The shielding can be accomplished with thin sheets of material, but the surface area to be shielding is much larger as one moves away from the source. For this approach, lightweight magnetic materials should be identified and configurations investigated, e.g. multiple spaced thin shields versus a single thicker sheet. At the higher level, the weight penalties associated with the two passive approaches, self-shielding magnet and large surface area shielding, can be compared and design trade-offs identified.

On an electrodynamic maglev vehicle, a 77K thin film superconducting shield would require very little additional power for cooling. Unfortunately, the high temperature superconducting YBaCuO thin films must be highly oriented with very few grain boundaries. Current fabrication techniques may not scale to the large areas required for maglev shielding. Use of high $T_c$ thin films as passive shields requires development of large surface area coating techniques. In addition, the physical upper limit on the critical field level of YBaCuO superconducting material appears to be about 100 gauss. The upper limit on the low critical field level limits application of this shielding method to low field levels less than 100 gauss. This limit may be met in a hybrid shielding configuration where a small amount of high permeability material shields the field below 100 gauss, and the thin film superconducting film achieves very high attenuation of the remaining magnetic field.

For superconductor shielding of fields above 100 gauss, the flux pinning effects are critical. Shielding instabilities due to flux creep must be understood and the characteristic time constants of flux creep, the rate at which the magnetic field penetrates into the superconductor, should be determined. Development of fabrication techniques which produce superconductors with high critical field levels will also produce superconductors with excellent flux pinning characteristics.

An effort in the area of active shielding should address design methods for canceling a spatially varying field with the minimum current and coil complexity. A study such as this could utilize three-dimensional magnetic field analysis tools for determining coil locations and orientations which achieve the proper field attenuation with a minimum effect on the working magnetic field of the levitation and guidance magnets. Once again, hybrid shielding systems which use the strong points of both active and passive shielding methods should be investigated.

Reliability is an issue which should be addressed for all shielding methods mentioned above. A passive system of ferromagnetic sheets optimized for the typical operating conditions may not shield properly with the quench of one or more superconducting levitation and guidance magnets. Superconducting thin film passive shielding and active shielding using superconducting coils would both be rendered ineffective by cryogenic system failures. If a levitation magnet quenches, an active system must be turned off to avoid creating large uncancelled fields by itself.

## III. RECOMMENDED RESEARCH

The author recommends the following research areas with priorities ranked from 1 to 3, 1 being the highest priority:

1 A general study of various shielding methods which results in shielding characteristic curves and weight-power-reliability-cost trade-offs for various levels of magnetic field attenuation.

1 Determine activation energy constants and flux creep time constants of YBaCuO superconductor samples as a basis for evaluating high-temperature superconductor shielding above the lower critical field level $H_{C1}$. The information may be available from a survey of superconductor literature.

1 Develop fabrication techniques for producing large area high temperature superconducting thin films and determine the additional cryogenic power requirements.

2 Develop design methods for active shielding systems using 3D electromagnetic analysis software and apply these methods to determine the strengths of active shielding systems as well optimum coil size, location and orientation. This would include determining at what field levels, standard room temperature conducting coils would become impractical, necessitating superconducting compensation coils.

3 Investigate hybrid shielding systems which combine shielding methods to determine if combinations of the methods lead to lower weight/power/cost shield systems for various levels of stray field attenuation.

## IV. ACKNOWLEDGMENTS

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## MAGLEV SYSTEM CONCEPT USING 20-K HIGH-TEMPERATURE* SUPERCONDUCTORS

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### ABSTRACT

Magnetically levitated high-speed ground transportation (MAGLEV) has the potential to benefit the overall transportation infrastructure, provide more energy-efficient transportation, reduce the environmental effects of transportation, and reduce dependency on foreign energy supplies. Traveling at approximately 500 km/h (300 mi/h) for distances of up to about 650 km (400 mi), MAGLEV will most likely operate between hub airports in major cities. It is expected that both airport and highway congestion will be diminished as a result of successful implementation of this technology.

A major factor in the eventual incorporation of MAGLEV technology into the transportation sector will be the achievement of a low system capital cost. A major cost component of MAGLEV is the guideway, and a substantial fraction of this cost would be incurred in providing electrical power along the guideway for propulsion energy. In this paper, we explore the advantages and disadvantages of a specific MAGLEV concept that eliminates this requirement.

The MAGLEV concept discussed here employs liquid-hydrogen-cooled high-temperature superconductors (HTSs) for levitation magnets aboard the vehicle. The vehicle carries a large dewar of liquid hydrogen but no refrigerator. The guideway consists of a sheet of aluminum supported by a concrete structure. The vehicle is propelled by a short-stator linear induction motor (LIM). Electrical power is provided to the LIM from an air-breathing liquid-hydrogen turbine that drives a generator. Recent developments indicate that HTS wire may soon be available with current densities well in excess of 100 A/mm$^2$ in magnetic fields of 5 T and an operating temperature of 20 K. Such performance would be satisfactory for MAGLEV, and the superconductors could be cooled by liquid hydrogen.

There are a number of advantages inherent in this concept. The use of hydrogen as a fuel produces mainly water as an exhaust product. The hydrogen can be produced by a number of environmentally benign methods, and the energy cost of refrigeration to put the hydrogen in liquid form is relatively low compared to the fuel energy of the hydrogen. Relative to superconductors operating at 4 K, the 20-K HTSs should be inherently more stable and less subject to quench. Because the turbine is mainly used to generate

electricity, it can be enclosed in a sound-absorbing container, and the noise from the turbine generator should be insignificant compared to the aerodynamic noise of the moving vehicle. On the other hand, it may be possible to use part of the turbine exhaust to provide guidance, improve ride quality, and perhaps provide thrust in emergencies.

The main disadvantage associated with the use of liquid hydrogen seems to be a lack of experience in handling it, except for several special applications such as rocket engines and the production of hydrogenated margarine. While hydrogen-powered turbine generators are not common, the technology is a relatively straightforward extrapolation from conventional turbines.

The efficiency of the hydrogen-powered propulsion system is compared in this paper to more conventional methods of MAGLEV propulsion. Analysis covers generation of the hydrogen and conversion efficiencies at various stages of the fuel cycle. The size of the hydrogen tank, weight of the generator, and requirements for the LIM are given for several route configurations. Estimates for guideway costs are also compared to conventional systems. The availability of onboard propulsion power should simplify switching procedures.

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# EMERGING MAGLEV RESEARCH NEEDS

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## I. STATEMENT OF PROBLEM

High performance air core superconducting magnets inherently have a relatively large stray DC magnetic field. In addition, an AC field is generated by harmonics of the linear synchronous motor windings. These fields potentially create safety issues and nuisance issues. Personnel, baggage and SC magnets need shielding from AC and DC magnet fields.

Superconducting magnetic energy storage (SMES) devices represent an opportunity to reduce the cost of power for the maglev system. SMES devices are devices which store energy magnetically and, with the appropriate electrical circuits, can deliver the energy when it is needed. Power cost is driven by generation and transmission costs. Appropriate geographic siting of SMES devices potentially can reduce these costs significantly.

This paper will discuss two of the many emerging research topics for magnetically levitated trains, herein abbreviated maglev. These issues are magnetic field shielding and superconducting magnetic energy storage. The fundamental issue, however, is that these topics are NOT enabling technologies for maglev. Rather, the research described below will improve the safety and economy of the system. The maglev transportation system can move forward even as this research is pursued simultaneously.

## II. BACKGROUND

### Magnetic Field Shielding

High performance air core superconducting magnets inherently have a relatively large stray direct current (DC) magnetic field. In addition, an alternating current (AC) field is generated by harmonics of the linear synchronous motor windings. These fields potentially create two safety issues and a third major nuisance issue. The first issue is the potential for effects on personnel of exposure to the stray magnetic field. This issue has been looked at many times by reputable investigators with contradictory conclusions. The second safety issue is the potential reduction of magnet stability due to field interaction with baggage or freight. Specifically, if particular baggage items can cause the superconductor (SC) magnets to quench accidentally, causing loss of levitation and guidance, the safety of the personnel is reduced. The nuisance issue is the possibility of stray magnetic fields inadvertently modifying magnetically recorded information or other magnetically sensitive equipment or influence adversely instruments. The magnetic stripe on credit cards, magnetic tapes, and delicate measurement apparatus immediately come to mind as likely objects which shielding should protect. In summary, personnel, baggage and SC magnets need shielding from AC and DC magnet fields.

Superconducting Magnetic Energy Storage (SMES)

SMES represents an opportunity to reduce the cost of power for the maglev system. SMES devices are devices which store energy magnetically and, with the appropriate electrical circuits, can deliver the energy when it is needed. Since the energy is stored in a superconducting device, there is no significant loss of energy as a function of time. Hence, energy can be accumulated in the SMES when it is available inexpensively and it can be used when energy would otherwise be expensive to provide. This is the idea behind utility load leveling. By siting the SMES near regions of significant grade, descending trains can generate excess energy which can be stored in the SMES for later use by an ascending train. Local SMES siting decreases electrical losses and power transmission costs.

Demonstration devices have shown that energy can be stored for many years in superconducting devices. For application to maglev, however, energy storage for days without significant loss is all that is required.

Magnetic Field Shielding

Exposure limits need to be defined in terms of magnitude, frequency and duration. Duration is not important for baggage or the SC magnets, but may be important for baggage or the SC magnets, but may be important for personnel. Specifically, train attendant and passenger exposure differences (if any) need to be determined. Shielding must protect personnel during transit and while loading and unloading at a station.

Diamagnetic (Meissner) and ferromagnetic shielding materials need to be improved. Superconductors exhibit the Meissner effect which means they are inherently diamagnetic. There are two important parameters for shields made of superconducting materials: the lower and upper critical fields, Bc1 and Bc2 (note: Bc1 < Bc2). Below Bc1 there is perfect Meissner shielding, while above Bc2 there is no shielding effect and between Bc1 and Bc2 there is a partial shielding effect. Low temperature superconductor (LTSC) materials have been optimized for high field operation not for shielding applications (i.e., they have high values of Bc2 and low values of Bc1). Therefore, the shielding ability of LTSC can be improved by optimizing the metallurgy for this purpose, and specifically, by increasing the value of Bc1. Typically, these materials are used in wire form, although some efforts have results in thin sheet materials [David Fugate, Westinghouse, this Workshop].

High temperature superconducts (HTSC) discovered to date also have low values of Bc1 and very high values of Bc2. Nonetheless, HTSC materials offer the hope of room temperature Meissner shields. HTSC are readily produced in thin sheet form suitable for shield. Control of crystal orientation during fabrication will improve the performance and, by increasing the yield, will reduce the cost of today's materials at liquid nitrogen temperatures. Lamination of HTSC materials, possibly with ferromagnetic interlaminate layers may be one embodiment of a shielding system. Research needs include increasing the lower critical field of HTSC materials and the ductility of the materials so that shield integration into the vehicle is simplified.

The saturation flux density of ferromagnetic materials needs to be increased and the ferromagnetic material density should be reduced. This will allow greater shielding capacity to occur in a lightweight material.

Shield system integration needs to be done so the benefit of shielding one area is not degraded by compromises in another area. In particular, station design needs to be carefully considered allowing shielded passenger entry and exit while the SC magnets are energized.

The engineering tradeoffs of shielding can be summarized as: increased vehicle weight and volume, increased power requirements, and generally increased vehicle costs. These compromises need to be minimized.

Figure 1 shows a candidate design for maglev passenger vehicle. As indicated in the figure, the SC magnets are at the ends of each individual vehicle. The advantage in this design is the inherent reduction in magnetic field intensity within the body of the vehicle due to the large distance from the magnets.

Figure 2 shows a plot of the worst-case (unshielded, along magnet centerline) field magnitudes in the plane of the passenger compartment floor. A constant-field line is indicated for convenience. Note that at approximately 4 m from the unshielded magnets the field intensity is 20 Gauss for a magnetomotive force of 1.4 MA-T in two anti-parallel coils. For vehicles significantly longer than 2 x 4 m = 8 m, the bulk of the passenger compartment has a greatly reduced field, and so only minimal shielding need be applied. This fact greatly reduces the shielding weight and power requirements. On the other hand, for short vehicles the field intensity is due to the superposition of fields from all magnets, and the field could be twice as great, or more, than indicated here. Figure 2 shows a plot of the worst-case field magnitudes in a plane parallel to the passenger compartment floor.

Four specific approaches to magnetically shielding the vehicle are presented in Figure 3. They are: HTSC with ferromagnetic material, LTSC with ferromagnetic material, Ferromagnetic material-only, and Resistive conductor with ferromagnetic material. To obtain very low stray magnetic fields all designs employ ferromagnetic materials. All thicknesses have been exaggerated in the figure for clarity.

HTSC with ferromagnetic material: Room-temperature SC materials with a large value of Bc1 would greatly reduce the shield weight while providing excellent shielding. HTSC materials can be already produced in thin sheets. These sheets could be installed in the vehicle near the superconducting magnets and along the length of the vehicle.

LTSC with ferromagnetic material: As with HTSC materials, the Meissner effect of LTSC conductors can be used to advantage to provide magnetic field shielding. Incorporating the shield conductor and supplying its cryogenic needs will require careful vehicle design and packaging. Note the Meissner effect is automatic--no power supply or persistent current switch is required. There may be fruitful design overlap in the main SC magnets and the shield magnets which will increase the reliability of both magnets.

Ferromagnetic material-only: Passive shielding weight for the field levels of a high performance superconducting magnet composed of today's ferro-magnetic materials is prohibitive in weight. A plate 20-30 mm thick with a mass of 6000 to 9000 kg would be required. Ferromagnetic materials of low density (say similar to that of lithium, 1/10 that of iron) could provide adequate shielding at acceptable weight.

Resistive conductor with ferromagnetic material: Room temperature normal conductors have the advantage of requiring no cryogenic coolant. However, the power dissipated resistively can be quite high--and the weight increases sharply as the conductor cross-section is increased to reduce power consumption. Typical numbers mass and dissipated powers are: 4000 kg and 4 MW or 2000 kg and 8.5 MW.

Superconducting Magnetic Energy Storage (SMES)

The cost of electric power has two major components: generation cost and delivery cost. The marginal cost of power generation is very high if additional generating capacity must be brought on-line to supply it. The marginal cost of power generation is greatly reduced if advantage can be taken of excess power generation capabilities. Therefore, it is desirable to accumulate power when it is available inexpensively and to use the accumulated power when it is required. This is the concept behind load leveling. In addition, locally storing the energy near the source/sink of energy reduces power transmission costs. SMES is one means of achieving reduced power costs.

Note that a maglev SMES will store an order of magnitude of a few gigaJoules, say 2-5 GJ = 550 kW-hr to 1.4 MW-hr. This is substantially less energy than a SMES proposed for general electric utility load leveling, which may to 100 to 1000 times larger.

There are other means available for supplying peak power demands such as rotating machinery. These alternative means are relatively well-developed, compared to SMES. Therefore, to intelligently chose among alternatives, SMES should be developed to the same level of development.

The goal of SMES is to save money. Therefore, the criterion is simply a comparison of the life cycle costs (LCC) of SMES versus the alternatives. A great deal of additional information is required before the LCC of SMES is known with any certainty. SMES designs need to be generated and these designs need to be integrated into the maglev system so that accurate LCC can be estimated.

Hill climbing at full speed always increases the power requirement. Hill climbing power can approximate or exceed aerodynamic drag power. The hill critical-slope is defined as that slope at which the hill climbing power is equal to the aerodynamic drag. Long-train maglev concepts have a lesser critical slope than short trains. Figure 4 shows a schematic of how a SMES device can source and sink excess power.

Longer trains have less aerodynamic drag per unit mass compared to shorter trains (other factors being equal). Hence, long trains reduce the energy cost per unit mass compared to short trains. On the other hand, long train maglev concepts have a greater peak power requirement than short trains. SMES devices can satisfy the peak power needs of long and short trains.

System engineering of SMES devices needs to be performed. This includes geographic siting, perhaps near regions of steep slope, and sizing of required stored energy. As mentioned above, the stored energy requirement for maglev is substantially less than that required for general electric utility load leveling.

To ensure that the maglev system achieves the technical goals at lowest cost, SMES system studies should be performed to quantify the required characteristics of a SMES. Performance parameters such as stored energy, structural mass, cryogenic cooling requirements, electrical circuits for energy transfer to/from the maglev system (presumably a linear synchronous motor (LSM)), etc. should be determined.

Two basic geometries have been considered for SMES: toroidal and solenoidal geometries. Toroids have the significant advantage of negligible stray magnetic field. Solenoids have the advantages of comparatively simple construction and minimum structural and conductor materials and so reduced costs. The Virial theorem establishes a lower limit on the structural mass required to contain magnetic energy. This is the concept of specific energy density, that is, energy per unit mass. The Virial theorem further states that this minimum structural mass must be used exclusive in tension--the required mass of the tension members is actually increased by the mass of the compression members. For this reason solenoids have an inherent material and, therefore, cost advantage over toroids of approximately a factor of 2-2.5. Foster-Miller, Inc. has recently completed a design study of a solenoidal cryogenic inductor specifically designed to limit conductor strain. For a strain limit of 0.5%, our design achieved a specific energy density ratio of 150 kJ/kg.

Based upon our design studies SMES devices can be built and operated in a cost-effective manner. The public's concern about the effect of external magnetic field suggests the SMES should be toroidal with negligible external magnetic field.

Transferring the stored energy from the DC SMES to the AC LSM is a practical necessity. Proprietary electrical circuits have been developed (Y. Eyssa, Univ. of Wisconsin, private communication) which provide for a very high DC-DC transfer efficiency, approaching 95%. Conversion from DC-AC is still necessary and can be accomplished with standard GTO-based circuits.

## III. CONCLUSION

In conclusion, two emerging research needs for maglev have been presented. The goals of increased safety and operating economy justify research in these areas. Magnetic field shielding is important for passengers, baggage and for protection of the superconducting magnets. A system's approach representing an intelligent integration of improved materials and designs is required. Magnetic field exposure limits must be established for detailed designs to be performed.

The cost of energy is an important parameter for maglev economics. Superconducting magnetic energy storage (SMES) is one possible way of reducing the cost of power generation and transmission. Research into SMES is needed to gain information which can form the basis for intelligent decision-making. SMES research is justified by the potential for cost savings.

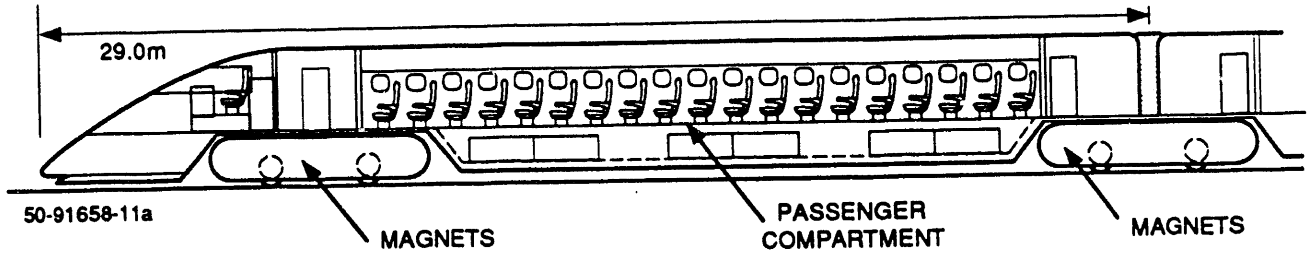


Figure 1. Magnets, People, Magnets, People

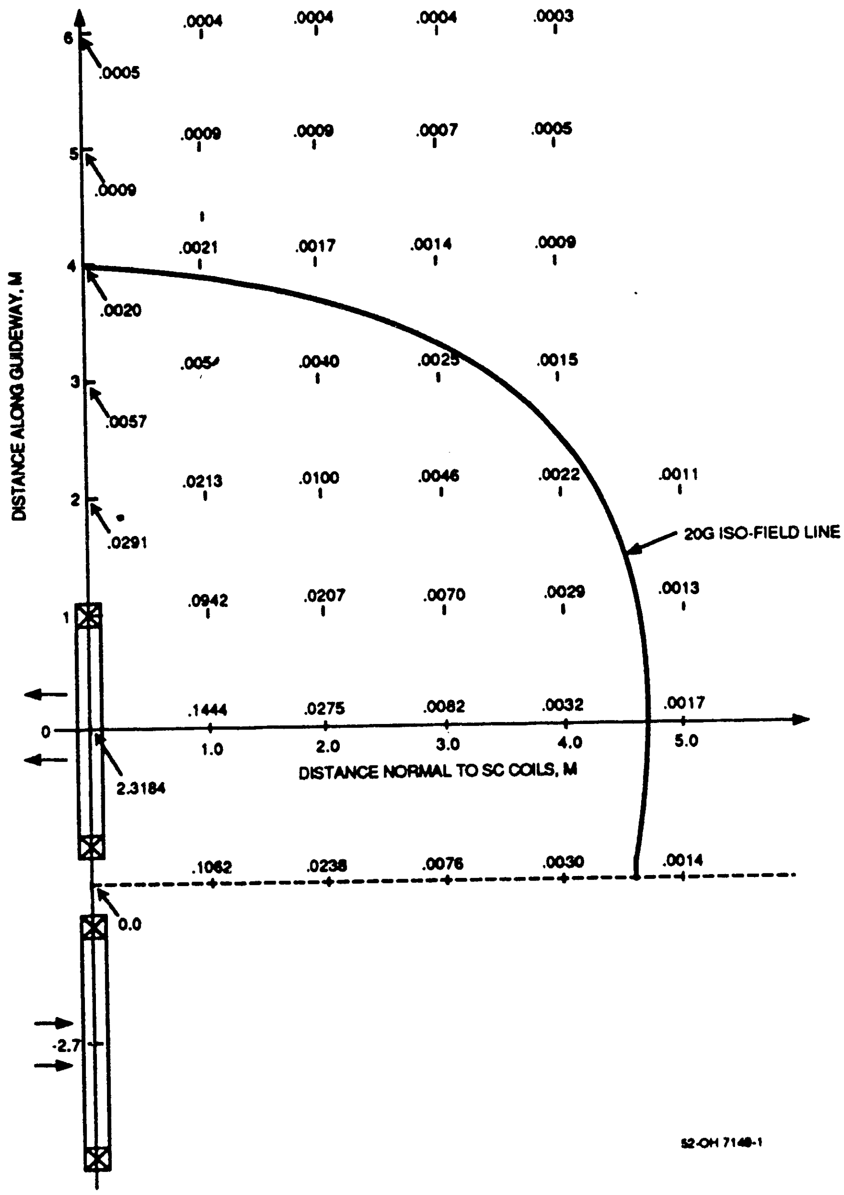


Figure 2. Worst-Case Magnetic Field Magnitude

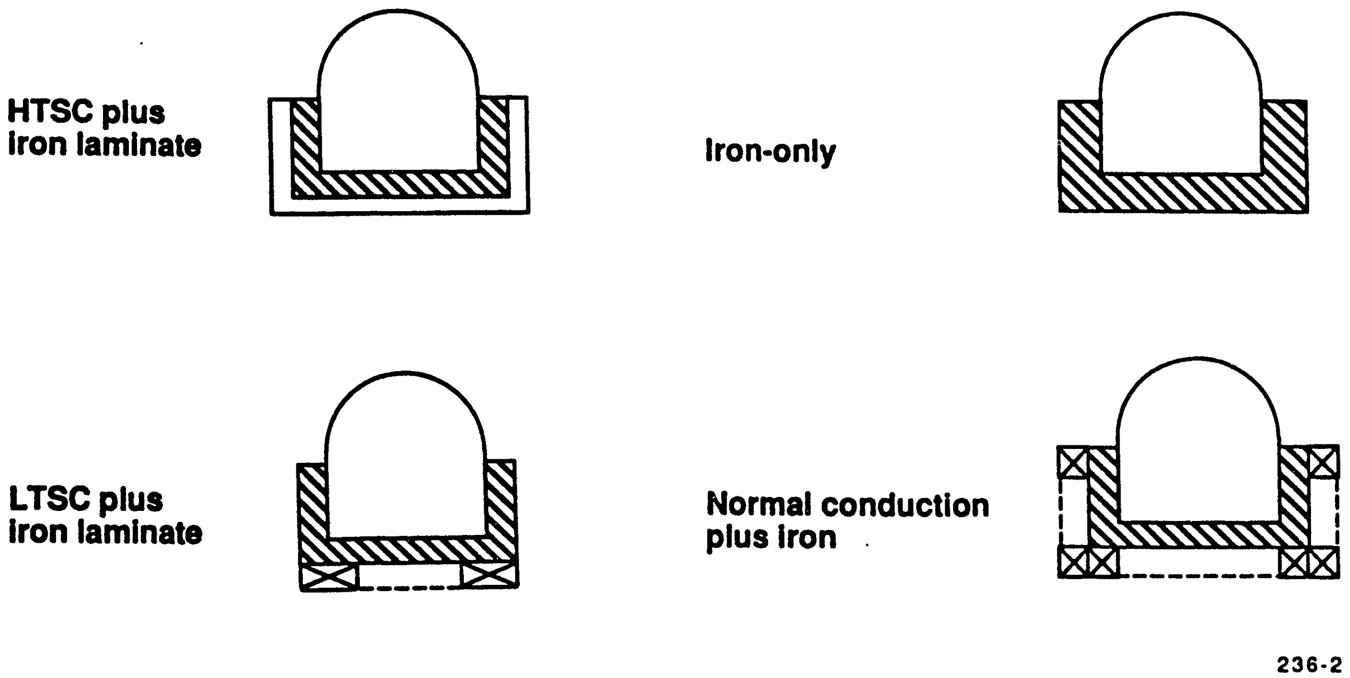


Figure 3. Approaches to Magnetic Field Shielding

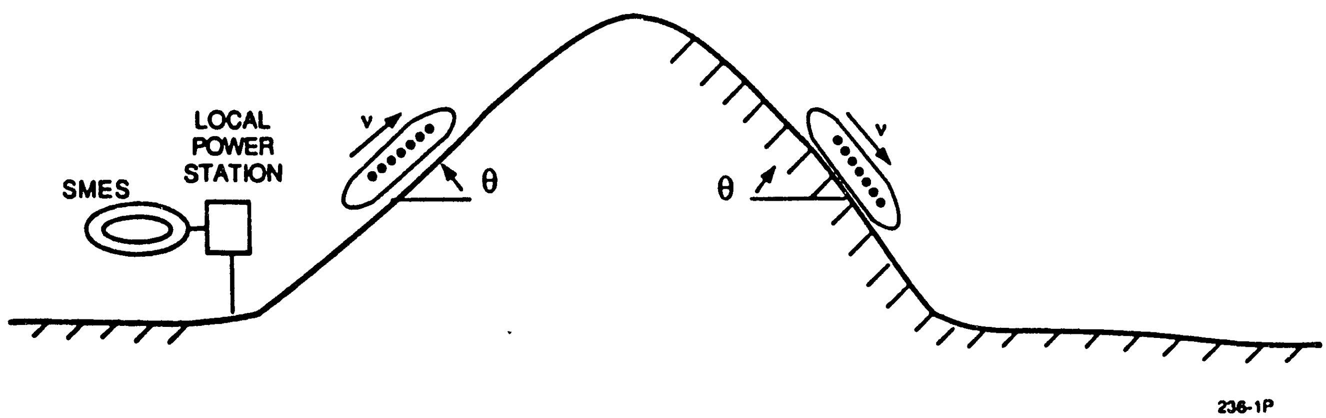


Figure 4. SMES Schematic

## MAGNETIC SHIELDING IN MAGLEV

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### I. STATEMENT OF PROBLEM

MAGLEV is distinctive in the large number of design options available for optimization. The magnetic fields induced in some of these options are described by detailed simulations of magnetic fields before and after shielding[1]; while for other options, actual measured values from test systems are available. Calculated direct current (DC) field strengths, inside the vehicle cabin, are over 50 mT (500 Gauss) in some designs using superconducting magnets[1]; while in TRANSRAPID 06, which uses permanent magnets, DC fields inside the vehicle cabin have been recorded at smaller strengths of 0.1 mT (1 Gauss) at floor level. Corresponding alternating current (AC) fields fell from 0.02 mT (0.2 Gauss) at low frequencies to 0.2 $\mu$T (2 mGauss) between 200 and 400 Hz[2].

There is some doubt concerning what the public will tolerate as acceptable risk with respect to unfamiliar DC and AC fields.

Among the most critical of documented effects[1] are the effect of DC fields on some designs of cardiac pacemakers where relays trip at external field strengths of 1 mT (10 Gauss). Higher fields can interrupt digital magnetic storage, control switching and electronic consumer goods. Various National Laboratories have adopted different safety standards for workers wholly or partly exposed to magnetic fields for short or long durations[1]. A safe level occurs between the above value and the earth's magnetic field of 0.04 mT (0.4 Gauss).

Biological consequences of applied AC fields are frequently disputed[3]. Under high voltage transmission lines magnetic field strengths can reach 0.3 Gauss with a frequency of 60 Hz. While there have been epidemiological studies reporting linkages between such fields and various forms of cancer, the statistical significance seems to be generally regarded as inconclusive[3]. However biochemical observations suggest more subtle effects which could be carcinogenic, and a safety standard for public exposure has not so far been agreed. The standard will most likely lie above a typical domestic field strength of 1 $\mu$T (0.01 Gauss).

A severe penalty is involved in reducing the magnetic fields in a MAGLEV cabin much below 2 mT (20 Gauss) by conventional shields[1,4]. The cost includes not only vehicle construction, but more importantly, the capital cost of guide-rails, since these structures depend on the vehicle weight. The cost can, apparently, be alleviated by new materials with known properties[5].

In summary, it is known that magnetic fields pose a health problem in MAGLEV. The field strengths, both DC and AC, are predictable. They can be shielded but at the expense of increased vehicle weight. Safe levels for both DC and AC fields, especially the latter, are not yet finally determined.

## II. BACKGROUND

### a) Simulations

It is essential that computer simulations are undertaken for proposed designs, particularly of lifting magnets, but also of guidance and propulsion magnets. These simulations should identify the strength of fields not only in the vehicle cabin in motion, but also when stationary at platforms. The simulations should include finite element methods for simulating the shielding factors of (1) ferromagnetic shields, (2) eddy current shields, (3) active shields, and (4) superconducting shields.

The simulations can be used to determine shielding factors, both AC and DC, for shields of various geometries, and made of various materials. With parametrization of key design parameters, critical points can be identified and the weight-cost determined which is necessary to shield the fields within specified limits.

### b) Materials

Since new materials are available for magnetic screening, careful materials selection is required for both the DC and AC components. Figures of merit should be determined for shielding factors with respect to weight, including, as appropriate, cryogenic requirements for particular shielding configurations. Where properties of promising materials are inadequately known, confirmation is required, particularly with regard to shielding factors to be found within applied fields of strengths and frequencies encountered in MAGLEV.

### c) Standards

Research is required for two purposes, firstly to progress towards identifying and verifying safe levels for long term exposure to DC and AC magnetic fields, and secondly for ready access to data for swift information response if demanded. As a starting point, critical analysis of various standards adopted by National Laboratories[1] can be used to set an initial limit, with further limitation dependent on future research results and perceived shielding capabilities.

## III. RECOMMENDED RESEARCH

### a) Simulation of magnetic fields

Parametric studies are planned to determine the cost incurred by mitigating approaches. Since magnetic fields are generally undesirable, inflections will be identified so as to reduce the fields as much as possible within economic constraints. These studies will keep abreast of public and scientific discussion of appropriate standards. Initially, the weight-cost of vehicle design will be determined to achieve a maximum static DC field of (a) 5.0 mT (50 Gauss), (b) 0.5 Mt (5 Gauss) and (c) 0.1 mT (1 Gauss), and a maximum AC field of (a & b) 0.1 mT (1 Guass) and (c) 0.01 mT (0.1 Gauss) at the floor level in areas of the vehicle where passengers and crew will be seated, and similarly for passengers standing on station platforms and egressing the vehicle.

The simulations will require the development of new code, based on finite element methods, especially for describing superconductive shielding. In this case the boundary condition requires lines of force to run parallel to the magnetic shields, in contrast to that in the case of ferromagnetic shielding, where lines of force are normal to the shield boundary.

The computer simulations will be used to parametrize shielding factors corresponding to weights of selected shields and vehicle geometrics. The frequency response of AC shields will be determined. Programs will be developed or adapted to describe intensities and spatial distributions of (1) unshielded fields, both before and after (2) shielding by superconductive flux exclusion. These fields will be compared with those described in the literature, calculated with (3) passive ferromagnetic shielding by flux concentration, or with (4) shielding by active coils. Finally recommendations will be made about the desirability of (5) combinations of these shielding techniques with alternative magnet geometries.

Detailed simulations will depend partly on the materials properties described below.

b) Optimization of shielding materials

Materials selection procedures are planned with special reference to the four conventional types of magnetic shield and of known properties of high temperature superconductors:

- Ferromagnetic shields or yokes (with some AC shielding) provided by high permeability materials[6] (e.g., Mumetal). Shields have a low magnetic reluctance in DC fields, but the reluctance increases in AC with increasing frequency. The required shield thickness is determined by the saturation field, $B_s$. The thickness, D, of shield needed to screen a field extended over height h, with average strength B is given by,

  $$D = Bh/B_s. \quad (1)$$

  Calculations show that 2 cm thick high-silicon sheet steel with $B_s = 1.2$ T (12,000 Gauss) will shield DC fields of 200 Gauss to fields below 2 mT (20 Gauss) in the vehicle cabon[3]. The weight of such shielding is 160 kg $m^{-2}$.

- Eddy current shields for AC, typically of Aluminum[3]. Shielding occurs within a skin depth,

  $$\delta = (\pi \sigma f \mu \mu_0)^{-1/2} \quad (2)$$

at frequency f, where $\sigma$ and $\mu\mu_0$ are the conductivity and permeability of the aluminum, for which $\delta \sim 8.4 f^{-1/2}$ cm. The amplitude of electromagnetic waves decays with depth, x, inside the metal as $\exp(-x/\delta)$. Thus a field intensity with frequency 500 Hz is reduced by 100 in a thickness of 8 mm weighing 24 kg $m^{-2}$.

- Active coils to counteract external fields and controlled by sensors[3] (see below).

- Superconducting shields, operating close to the temperature of liquid helium, e.g. at T<15 K for $Nb_3Sn$[7]. Such shields are effectively active because induced surface currents annihilate magnetic field within the superconducting material. The thickness of material needed for perfect shielding depends on the penetration depth, l(T), which is proportional to temperature as $1-(T/T_c)^4$ [4]. The shields can be made as thin as $25 \times 10^{-6}$ m, provided they are sufficiently homogeneous and that mechanical strength is provided by a substrate. The shields are efficient at screening both DC and AC. The chief weight factor involved in the use of conventional superconductor shielding lies in the cryogenic engineering.

- High $T_c$ systems

  Comparatively simple cryogenic insulation for the high $T_c$ systems offer much greater design flexibility than is possible for conventional superconductors. This is particularly true if the shields dual as the outer temperature shield of the superconducting magnets. The critical transition temperature of $YBa_2Cu_3O_{7-x}$, $Bi_2Sr_2Ca_2Cu_3O_{10}$ and $Tl_2Ba_2Ca_2Cu_3O_{10}$ are 93, 110 and 125 K respectively. Published data show that high shielding factors observed[8,9] (at frequencies 0.1<f<1000 in an external field of B<0.1 mT (1 Gauss) and specimen temperature of 77 K) are justified by measured materials properties including the critical fields, $H_{c1}$[10] (fields of 100 Gauss, 10 mT, are shielded at 40 K) and $H_{c2}$[11], and critical current density, $J_c$[12,13]. Shielding occurs even when the applied field is greater than $H_{c1}$, as described by the Bean model[14]: there is a region of zero field inside the superconductor if the applied field,

$$B^* < \mu_0 J_c D/2, \qquad (3)$$

  where $\mu_0$ is the permeability of free space, $J_c$ is the critical current density of the specimen and d is its thickness (see figure 1).

Table I shows a comparison of shield weights necessary to shield applied fields of strength 0.06 T (600 Gauss) DC or of strength 0.1 mT (1 Gauss) AC. More detailed characterization is required, and also materials development. While current high temperature superconducting materials are viable for this application, further processing by grain-growth and alignment are known to provide materials with enhanced critical current density[15,16,17] and flux trapping[18].

c) Standards

Experiments are planned in collaboration with the Health Sciences Center at Stony Brook to assess biological effects of Ac magnetic fields. These will

complement research initiated by the Department of Energy, the National Science Foundation, the National Institute of Health, etc.

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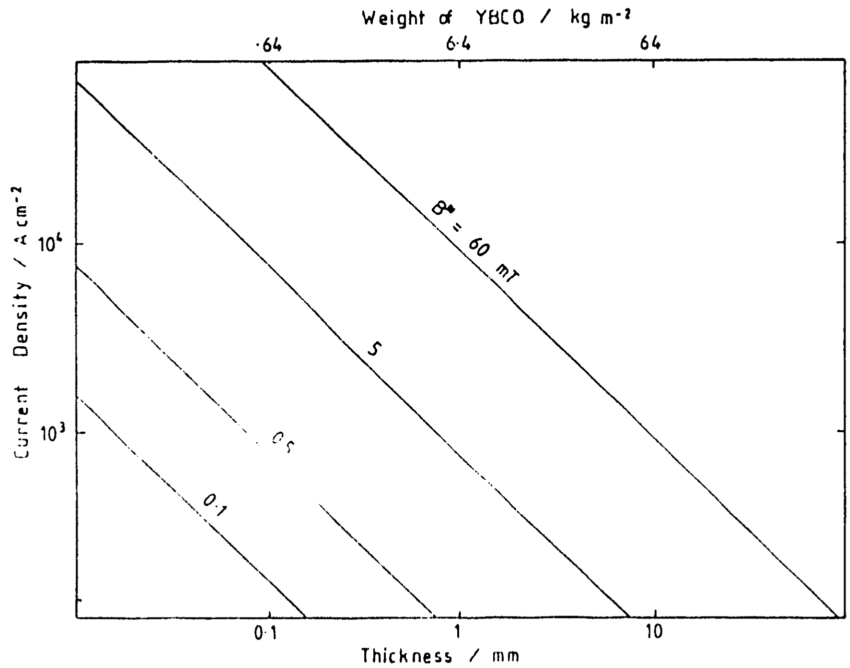


Figure 1. Relationship between current density, shield thickness and applied field, $B^*$, derived in equation 3. Also shown is the weight per $m^2$ of a shield made of $YBa_2Cu_3O_{7-x}$, dependent on thickness and density. The other superconductors described have similar densities.

Table I. Shield weights necessary to shield applied DC magnetic fields of strength 0.06 T.

| | Ferro-magnetic DC | Eddy Current AC | Superconducting Conventional DC and AC | High $T_c$ Best Case | Worst Cast |
|---|---|---|---|---|---|
| $J_c$ [a]/$Acm^{-2}$ | - | - | $10^5$ | $10^5$ | |
| Thickness[b] /mm | 70 | 9 | $3x10^{-3}$ | 0.094 | 47 |
| Weight /kg $m^{-2}$ | 560 | 24 | 0.23[c] | 0.7 | 329 |
| Temperature /K | ambient | ambient | <15 | 77 | 30 |

[a] $J_c$ is a materials property, also dependent on temperature and applied magnetic field strength.

[b] Equations (1), (2) and (3). The factor 1/2 in equation (3) applies in uniform fields, but is close to 1 in a field gradient.

[c] The cryogenic container needed for this type of shielding has a weight comparable to that of the ferromagnetic shield, apart from the engineering difficulty involved in cooling large surfaces to requisite low temperatures.

# SIMULATION OF MAGLEV RIDE ENVIRONMENT

BY

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(SLIDES)

## MAGLEV RIDE SIMULATION: RATIONALE

- MAGLEV IS TECHNICALLY LESS CONSTRAINED THEN HSR. IT CAN
  - TRAVEL AT HIGHER SPEEDS
  - USE ELEVATED GUIDEWAYS
  - ACCELERATE/DECELERATE FASTER
  - NEGOTIATE TIGHTER CURVES
  - TRAVERSE ROLLING TERRAIN BETTER
- MAGLEV'S GREATER FLEXIBILITY ALLOWS IT TO USE EXISTING ROW ALONG INTERSTATES & RR LINES, & SERVE MORE AREAS
- PASSENGER COMFORT WILL BE AN IMPORTANT FACTOR IN CHOOSING ALIGNMENTS AND LOCAL OPERATING SPEEDS
- RIDE ENVIRONMENT SIMULATION CAN HELP IN DETERMINING DESIGN GUIDELINES

SLIDE 1

# TOPICS

- PASSENGER RIDE ENVIRONMENT FOR OTHER TRANSPORT MODES
- MAGLEV ROUTES ALONG THE INTERSTATES AND IMPACT ON RIDE ENVIRONMENT
- CAPABILITY FOR SIMULATING MAGLEV RIDE ENVIRONMENT
- REMEDIATION TECHNIQUES
- CONCLUSIONS/RECOMMENDATIONS

SLIDE 2

# RIDE ENVIRONMENT FACTORS

| FACTOR | QUESTIONS |
|---|---|
| • LONGITUDINAL ACCELERATION/ DECELERATION | • MAGNITUDE? HOW OFTEN? |
| • LATERAL ACCELERATION/ DEGREE OF BANKING | • MAGNITUDE? HOW OFTEN? SINGLE OR ALTERNATING SEQUENCE OF BANKS |
| • VERTICAL ACCELERATION | • MAGNITUDE? HOW OFTEN? |
| • PERCEPTION OF PASSING TERRAIN | • CLOSENESS? PERCEIVED ANGULAR SPEED? |
| • PERCEPTION OF ONCOMING/ PASSING MAGLEV VEHICLES | • DISTANCE TO OTHER VEHICLE? FREQUENCY OF |
| • CABIN VIBRATION | • MAGNITUDE? FREQUENCY? |
| • CABIN NOISE LEVEL | • MAGNITUDE (dB)? |

SLIDE 3

## RIDE ENVIRONMENT FOR DIFFERENT TRANSPORT MODES

| MODE (OP SPEED) | LONG. ACC/DECL. | LATERAL ACC/BANKING | PERCEPTION OF TERRAIN | PERCEPTION OF PASSING VEHICLES |
|---|---|---|---|---|
| AUTO (60 MPH) | ±0.3 g (0 to 60 MPH IN 10 SEC) | -0.1 to 0.3 g [800 to 2400 FT CURVE RADIUS @ 60 MPH] | USUALLY CLOSE | 120 MPH CLOSING SPEED -5 FT. SEPARATION FREQUENT |
| AIR (500 MPH) | ±0.3 g (0 TO 225 MPH IN 5000 FT) | 24 DEGREE BANKING [COORDINATED TURNS INFREQUENT] | USUALLY DISTANT | RARE |
| HSR (185 MPH) | ±0.02 g | 12 DEGREE BANKING [TILT SUSPENSION MODERATELY FREQUENT] | VARIES FROM CLOSE TO DISTANT | 370 MPH CLOSING SPEED. -5 FOOT SEPARATION |
| MAGLEV (300 MPH) | ±0.15 g | 24 DEGREE BANKING [COORDINATED] | SAME | 600 MPH CLOSING SPEED -10 FOOT SEPARATION |

SLIDE 4

## OPTIONS FOR FOLLOWING EXISTING ROW

- CLOSELY COUPLED OPTION

  - GUIDEWAY CONSTRAINED TO EXISTING ROW
  - ACCEL/DECEL WHEN REQUIRED BY CURVES
  - MANY ACCEL/DECEL CYCLES
  - GUIDEWAY SPANS HIGHWAY FREQUENTLY
  - APPROACH USED IN GRUMMAN-NYS STUDY

- MODERATELY COUPLED OPTION

  - GUIDEWAY DEPARTS FROM EXISTING ROW AT TIGHT CURVES
  - REDUCED # OF ACCEL/DECEL CYCLES
  - GUIDEWAY SPANS HIGHWAY INFREQUENTLY
  - 10-20% NEW ALIGNMENTS ALLOWED

SLIDE 5

## MAGLEV LONGITUDINAL ACCELERATION/DECELERATION

- LONGITUDINAL ACC/DECEL PERCEPTION SHOULD NOT CONSTRAIN STATION
    - OFF-LINE LOADING/UNLOADING & HIGH SPEED SWITCHING APPEAR POSSIBLE
- LONGITUDINAL ACC/DECEL PERCEPTION MAY CONSTRAIN ABILITY TO FOLLOW EXISTING ROW OR REQUIRE LOWER AVERAGE SPEED
- PERCEPTION COULD LIMIT (NUMBERS ARE ILLUSTRATIVE, NOT FIRM)

1. # OF ACC/DECEL CYCLES PER HOUR (E.G. ~.10)

OR

2. FRACTION OF TRIP TIME IN ACC/DECEL MODE (E.G. ~10%)

- AT ~0.15 G TEMPORARILY DROPPING FROM 300 MPH to 200 MPH TO BETTER NEGOTIATE CURVES ON AN EXISTING ROW COULD BE CARRIED OUT 10 TIMES PER HOUR UNDER CRITERION #1, BUT ONLY 6 TIMES UNDER CRITERION #2

SLIDE 6

## CAPABILITY TO SIMULATE MAGLEV RIDE ENVIRONMENT

| FACTOR | NEAR TERM EXISTING SIMULATORS | NEW "HIGH FIDELITY" MAGLEV SIMULATION |
|---|---|---|
| CABIN SIZE | AIRCRAFT COCKPIT SIZE AND TYPE | FULL VEHICLE CROSS SECTION 1/2 TO FULL VEHICLE LENGTH MULTIPLE WINDOWS |
| MAX LONGITUDINAL ACCELERATION | ±0.3 g FOR SHORT PERIODS | ±0.3 g FOR ~2 SEC* (6 METER TRAVEL) |
| MAX VERTICAL ACCELERATION/ BANKING | ±24 DEGREES [W/LATERAL ACC. FOR SHORT PERIODS] [W/O LATERAL ACC. INDEFINITELY | ±24 DEGREES* [W/LATERAL ACC. FOR ~1 (SECOND)] [W/O LATERAL ACC. INDEFINITELY] |
| MAX VERTICAL ACCELERATION | ±0.1 g FOR SHORT PERIODS | ±0.1 g FOR ~2 SEC.* (2 METER TRAVEL) |

*ACTUAL ACCELERATION TIMES EXPERIENCED BY MAGLEV PASSENGERS WILL BE ~10 TIMES GREATER.

SLIDE 7

## CAPABILITY TO SIMULATE MAGLEV RIDE ENVIRONMENT (CONTINUED)

| FACTOR | NEAR TERM EXISTING SIMULATORS | NEW "HIGH FIDELITY" MAGLEV SIMULATION |
|---|---|---|
| WINDOW VIDEO DISPLAY | PARTIAL FIDELITY FOR TERRAIN, BANKING & PASSING VEHICLES | FULL FIDELITY FOR TERRAIN, BANKING & PASSING VEHICLES WITH MULTI-WINDOW DISPLAY |
| CABIN NOISE/ VIBRATION | EXPECTED LEVELS | EXPECTED LEVELS |

SLIDE 8

## REMEDIATION TECHNIQUES

- PHYSICAL
  - REDUCE SPEED AT SELECTED LOCATIONS
  - TEMPORARILY DEPART FROM EXISTING ROW
  - ENHANCE SEAT COMFORT (DEEP PADDING, EXTRA SPACE, ADJUSTABLE, ETC.)
  - COMPARTMENTING INSIDE VEHICLE
- PSYCHOLOGICAL
  - INDIVIDUAL TV SCREENS ON SEAT BACKS - CAPABILITY FOR STANDARD CABLE CHANNELS, GAMES, SPECIAL FEATURES, ETC.
  - CONTROL WINDOW SIZE/TRANSMISSIBILITY (SHADING)
  - ATTENDANTS (NUMBER?)

SLIDE 9

## CONCLUSIONS/RECOMMENDATIONS

- MAGLEV RIDE ENVIRONMENT APPEARS WELL WITHIN EXISTING ENVELOP OF PRESENT TRANSPORT MODES

- PRINCIPAL QUESTIONS ABOUT THE RIDE ENVIRONMENT ARE THE

  - DEGREE AND FREQUENCY OF GUIDEWAY/VEHICLE BANKING
  - FREQUENCY OF CHANGES IN VEHICLE VELOCITY TO ACCOMMODATE LOCAL SPEED CONSTRAINTS

- RIDE SIMULATORS CAN PROVIDE USEFUL INFORMATION ABOUT PASSENGER ACCEPTANCE OF VEHICLE VELOCITY & BANKING MANEUVERS

  - USE EXISTING AIRCRAFT SIMULATORS FOR PARTIAL FIDELITY STUDIES
  - BUILD NEW, FULL-SIZE SIMULATOR FOR "HI-FIDELITY" STUDIES

- REMEDIATION TECHNIQUES TO ENHANCE RIDE ENVIRONMENT SHOULD BE INVESTIGATED

- SIMULATION STUDIES WILL BE HELPFUL, BUT CANNOT FULLY DUPLICATE ACTUAL RIDE ENVIRONMENT - STILL NEED TEST TRACK(S)

SLIDE 10

# MAGNETIC AND CRYOGENIC SUBSYSTEMS FOR MAGLEV

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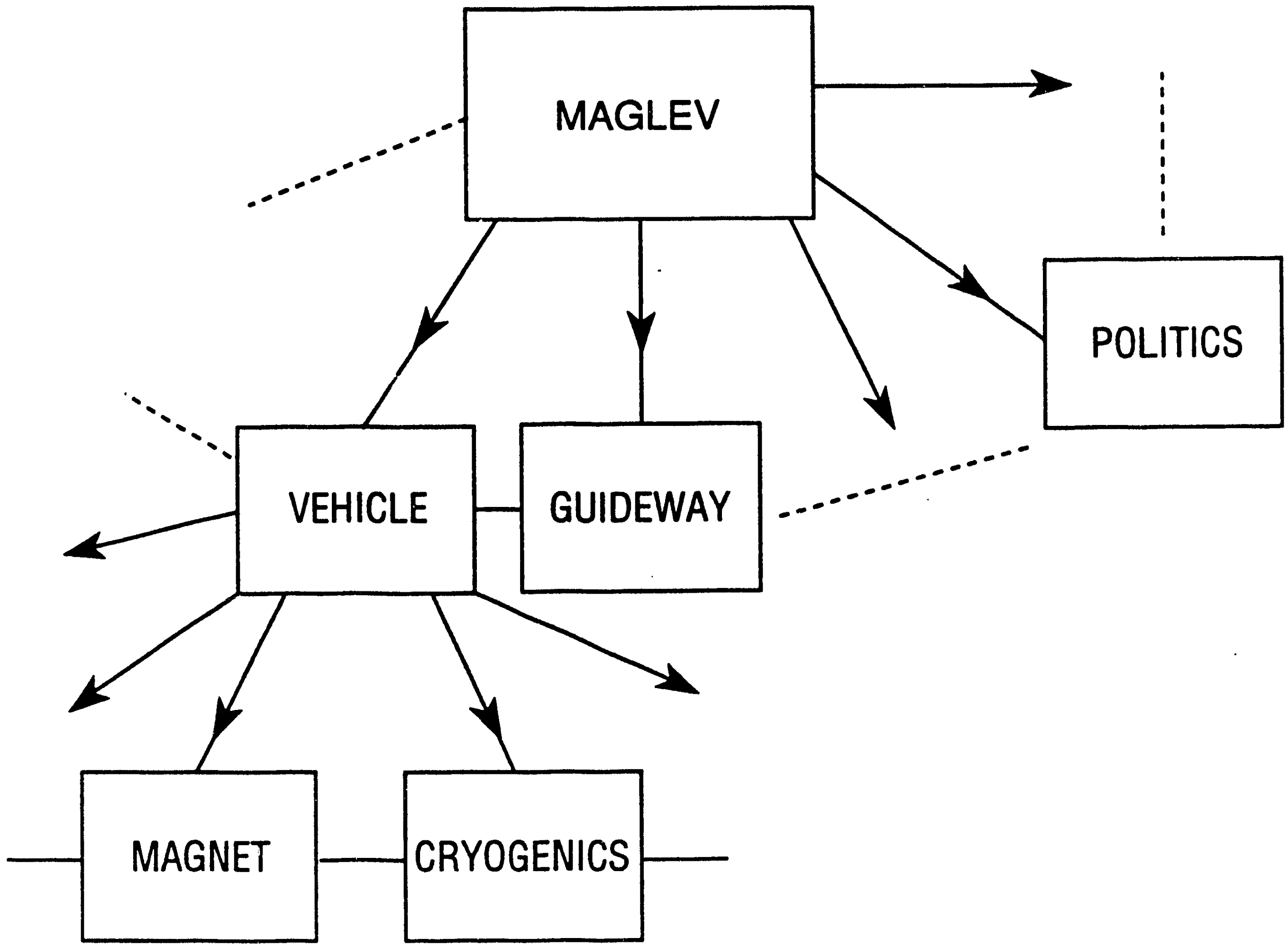
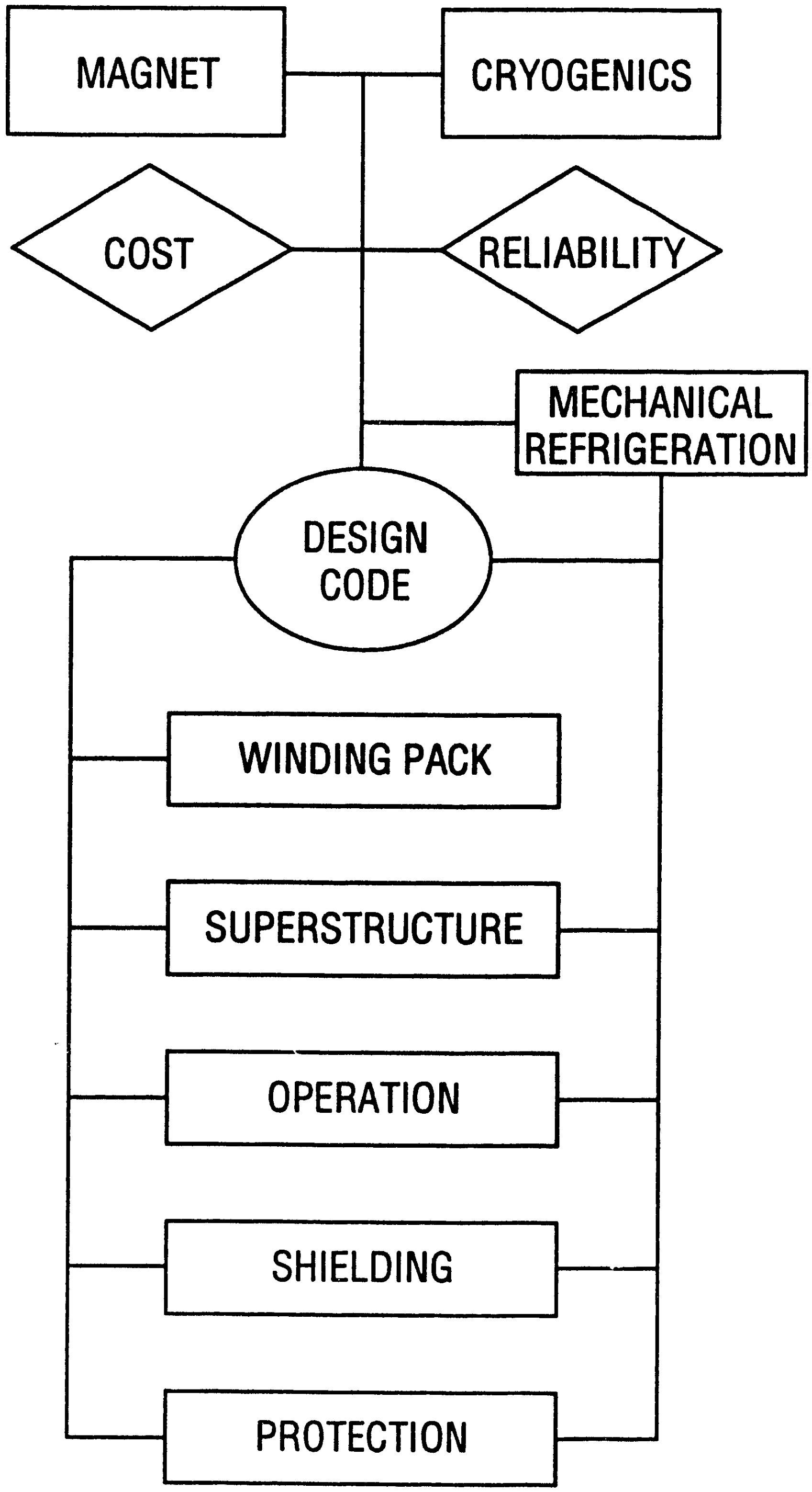
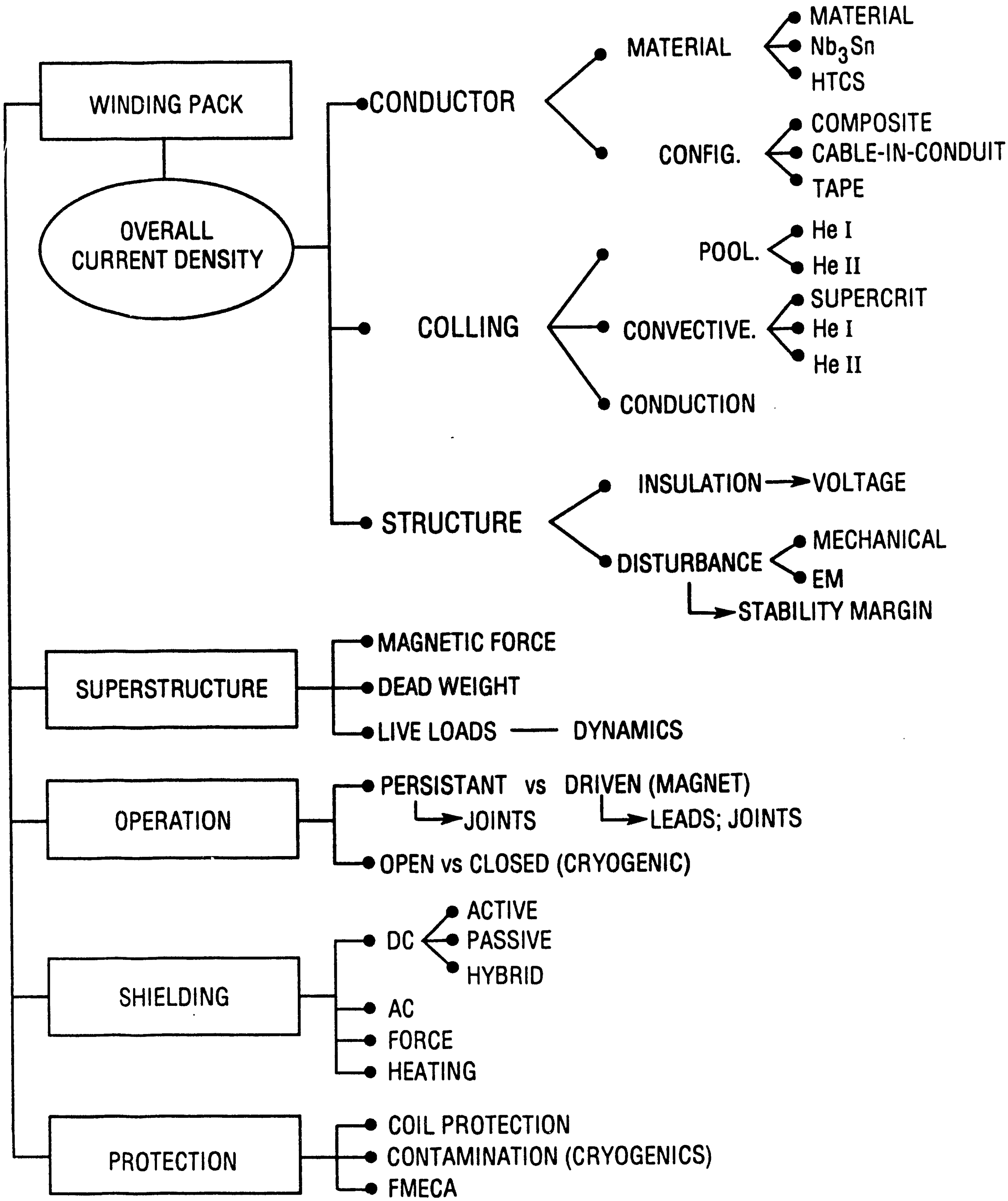



**SLIDE 1**


MAGNET
CRYOGENICS
COST
RELIABILITY
MECHANICAL REFRIGERATION
DESIGN CODE
WINDING PACK
SUPERSTRUCTURE
OPERATION
SHIELDING
PROTECTION

**SLIDE 2**


WINDING PACK
OVERALL CURRENT DENSITY
CONDUCTOR
MATERIAL
MATERIAL
Nb3Sn
HTCS
CONFIG.
COMPOSITE
CABLE-IN-CONDUIT
TAPE
COLLING
POOL.
He I
He II
CONVECTIVE.
SUPERCRIT
He I
He II
CONDUCTION
STRUCTURE
INSULATION
VOLTAGE
DISTURBANCE
MECHANICAL
EM
STABILITY MARGIN
SUPERSTRUCTURE
MAGNETIC FORCE
DEAD WEIGHT
LIVE LOADS
DYNAMICS
OPERATION
PERSISTANT vs DRIVEN (MAGNET)
JOINTS
LEADS; JOINTS
OPEN vs CLOSED (CRYOGENIC)
SHIELDING
DC
ACTIVE
PASSIVE
HYBRID
AC
FORCE
HEATING
PROTECTION
COIL PROTECTION
CONTAMINATION (CRYOGENICS)
FMECA

**SLIDE 3**

**MAGNET RESEARCH REQUIRED FOR MAGLEV**

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## I. STATEMENT OF PROBLEM

The accepted state-of-the-art magnet designs for maglev are the repulsive and attractive systems. The German Transrapid[1] full scale prototype has been in operation on a 20 mile test track for several years. It has a tolerance of one centimeter clearance between the rail and the moving car. It demonstrates the attractive method of maglev and does not involve superconducting magnets. The repulsive design is best illustrated by the Japanese National Railways system,[1] which has been tested as a full scale prototype on a four mile run and is being constructed on the Tokyo/Osaka run for 30 miles of the 300 miles. This will be completed in 1994. The superconducting magnetic repulsive system levitates at approximately 7 to 10 centimeters. Experience from MRI magnets makes possible operation of the superconducting magnets in a persistent mode for long periods of time and with very low helium loss rate, such that replenishment of helium and recharging of the magnet current can be infrequent. Because of MRI, small helium refrigerators have been developed to handle very low heat leaks.

There is some concern that microtesla fields with a frequency of ten to a thousand hertz can affect the calcium ion transfer between living cells.[2] This could have affects on cancer rates. Therefore shielding the fringe field is of utmost importance in the maglev passenger cars.

The development of high temperature superconductivity should be followed closely since this would made the superconducting magnets easier to construct. However, the long experience that has been developed for liquid helium magnets, makes it feasible to use helium cooled magnets.

## II. BACKGROUND

The information required for the development of maglev magnets and cryogenics is as follows:

- An optimum superconducting wire must be developed for use in the magnets.

- Magnet configuration on a car must be simulated to encompass all possible magnet failures.

- Optimization of the field required as a function of minimum drag must be considered.

- The structure of the magnets and where they can be placed under the car, affects very much the structure of the car. This must be studied.

- The support system for the magnets will need new innovations to keep the heat leak low.

- Very low magnetic field will be required in the passenger car; therefore, shielding the field is very important.

- The cryogenic problem must be made negligible, as is achieved today in MRI.

## III. RECOMMENDED RESEARCH

The recommended research would be along the following lines:

- We take the premise that the U.S. must develop the technology to manufacture the magnet, cryogenics and trains. We want the jobs of engineering and technology, and not just the jobs of sweeping the floor and selling hotdogs along the line. Therefore, I do not consider buying foreign technology an alternative.

- Industry has spoken clearly that they cannot support the R&D[3], therefore government must support the R&D needed to develop this technology.

- Since universities are the source of our scientists, they must be involved in the design and development of the technology. Thus far, this has been overlooked by the federal government by having too much emphasis on industry and national labs.

The recommended research can follow what has been initiated by the federal government. The recent request for proposal DTFR53-91-R-00021 Maglev System Concept Definition can be used to define the different systems possible. Once these different systems with different magnets are defined, government contracts should be let to test all of the different kinds of unit magnets. It should be pointed out that Fermilab had a working superconducting accelerator in 1983; however, SSC magnets were not finalized from R&D until 1991, eight years later. There is time now to look at all of the different concepts and to find the very best. In this manner, the U.S. can leapfrog foreign competition. These studies should include research on to define the following:

1. Research on the superconducting wire to be used, including filament size, current levels, stabilizer-to-superconductor ratio, eddy current problems because of vibration of the magnets in a field.

2. Superconducting switches need to be designed and tested.

3. Magnet structure must be tested to permit very reliable operation without quenching.

4. The size of the magnet must be determined to optimize lift and drag.

5. Guidance and levitation must be considered in an optimum configuration.

6. Support within the cryostats, warm-to-cold, must be studied and tested.

7. Supports between the magnet and the car must be considered since this effects the overall weight and fringe field considerations.

8. Shielding of the magnetic fields is one of the most important considerations.

9. Low heat leaks and small refrigerators must be considered.

The recommended research to test these features is construction of a unit magnet system with thorough testing including vibration on shaker tables. Background fields may be necessary to simulate reality. Following this unit magnet development program, which could be achieved in two years, I would recommend a second phase which would be the construction of a 20 mile test facility to test the best candidates of complete systems; magnet, propulsion and vehicle system. During the first 2 year phase, a guideway design could be selected for all of the various magnet systems. I would propose that this 20 mile guideway be constructed at the train testing center in Pueblo, Colorado, since the infrastructure is already available there. This location represents the various weather conditions that would be encountered. Grades and tunnels could be incorporated if desired. Two to five different systems could be constructed to operate on this 20 mile oval track. This part of the system could be done in three years. Therefore, at the end of five years, completely tested, full scale prototype systems would be available for implementation into actual rail systems throughout the country.

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# DEVELOPMENT OF 1) CABLE IN CONDUIT CONDUCTORS AND OF 2) AN APPROACH TO FMECA FOR MAGLEV MAGNET SYSTEMS

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## Cable in Conduit Conductor (CICC) for MAGLEV Magnet Systems

### I. STATEMENT OF PROBLEM

There are three basic options for cooling superconducting coil systems using the so-called low critical temperature (Tc) materials available today. Two of the options involve using helium as the working fluid around the conductor since it is the only material which does not solidify at the operating temperature required (i.e., about 4K). The most common choice is to immerse the winding in a bath of liquid helium operating at close to a saturation condition in which the helium can exist in two phases, liquid and vapor; the alternative is to raise the pressure above the critical pressure for helium (about 2.2 atm), thus operating in a "supercritical" condition in which only one phase is possible. The third option is to have a compact winding which is not directly in contact with helium, but which is cooled by conduction alone to a "cold foot" from a refrigeration system.

### II. BACKGROUND

Historically, cooling by immersion in a saturated bath at close to atmospheric pressure was the condition first studied experimentally and analytically to develop criteria and conditions for stable operation of superconducting coils. Local cooling capability for a conductor tends to be very high provided a nucleate boiling condition can be maintained when needed. This is often accomplished by reduction of the maximum possible heat flux generated and provision for liquid replenishment (i.e., prevention of dryout). Alternately, the winding can be designed to reduce destabilizing influences and cooled by conduction to a helium bath or the cold end of a refrigeration system, although the removal of heat generated due to AC losses can be a source of difficulty if the operation is not DC.

The two phase helium approach is complex for a MAGLEV system because of the continuously changing body forces due to acceleration, deceleration, elevation change, and curve execution. The result is a helium cryostat which must be baffled in a complicated fashion and which is subject to high losses because of sloshing of the liquid phase into "warm" sections of the vessel.

The approach based on conduction cooling to either a helium bath or the cold end of a refrigeration system may be difficult because of the losses generated throughout the winding as a result of the continuously generated field transients which can be expected from coil and track transverse relative motion.

A more favorable approach to superconducting coil design may be to use a conductor consisting of a cable of superconductors in a metal sheath. The sheath serves as a conduit for the helium coolant which flows in the interstices among the cable strands. If the pressure is above 2.2 atm, the helium can only exist in a single phase, hence the problems of controlling the liquid-vapor interface are eliminated. The stability and operating characteristics of this type of system have been under study for many years and demonstrated in coil systems much larger than those necessary for MAGLEV applications.

Early experiments with CICC demonstrated the advantages of the system from the operational stability standpoint. It has been the subject of investigations and development in laboratories throughout the world ever since (e.g., see [1.1 to 1.5]). Two (one using NbTi and the other Nb3Sn) of the six coils (approximately 40 tonnes each) in the Large Coil Test Facility have used the concept and it is the concept of choice for every large scale superconducting Tokamak now under consideration. In addition, a Nb3Sn conductor of this type was successfully tested recently in the US/Japan DPC Coil, a 2500 Kg, 7 MJ system designed and built by MIT. It experienced a maximum magnetic field of 10 Tesla and a maximum field sweep rate of 10 T/s.

A major advantage of using a Cable-in-Conduit-Conductor (CICC) for MAGLEV lies in the demonstrated ability to operate using a Nb3Sn superconductor in supercritical helium. The result is a conductor component with a very high stability margin that operates in a system with only a single phase working fluid. The latter is, therefore, not subject to sloshing due to G-load changes with the attendant high cryogenic losses, complicated baffling requirements and potential for "uncovering" the coil and increasing the probability of quench and system shutdown. A secondary advantage is that no separate helium vessel is required, thus leading to a less complex design. Furthermore, the working fluid temperature can be tailored to the conductor requirements as well as available cryosystem components since the operating environment is not at a two phase saturation condition. It is a natural configuration for an application such as MAGLEV.

In addition, the CICC configuration should be directly transferable to high Tc materials when they become available because any operating condition can be achieved with single phase helium provided the operating pressure & temperature are adjusted.

## III. RECOMMENDED RESEARCH

### Conductor Development

CICC conductors require cables of superconductor in vacuum tight conduits. Selection of materials, manufacturing process development and testing thus far have focused primarily on applications for large magnet systems for fusion where the operating current are tens of thousands of amps and the conduit is a significant structural component for accumulation and transmission of large static or low frequency dynamic loads within the winding pack.

AC losses are also an issue which has received considerable attention for transient requirements consistent primarily with fusion applications.

MAGLEV will require conductors which operate at low current levels with relatively modest static structural requirements, a substantially different dynamic load spectrum and a different exposure to transient magnetic fields leading to a different AC loss spectrum. The result is the need for R&D activities for manufacturing processes consistent with conductor requirements for low current (e.g., 100-1000 amp) and for conduits which can be applied in a cost effective fashion consistent with vacuum applications. Testing should concentrate on conductor performance in terms of energy margin, quench characteristics and AC loss generation. Alternative forms of conduit geometry and materials should be tested to include single and multiple flow paths.

Code Development

Codes for prediction of CICC performance in terms of energy margin, stability and quench have been under development for several years. They have been moderately successful in correlating with experimental results, but are not generally reliable for prediction and are not efficient in terms of computer usage, particularly for quench. A development activity in this area is essential for better understanding of CICC performance and for acceptable, efficient design purposes.

Joint & Lead Development

The CICC developed for MAGLEV will require reliable hydraulic manifolds and joints as well as electrical joints and connections to power leads. Although often perceived as mundane engineering problems, they are also the most likely source of magnet failures and require R&D early to assure reliability.

Persistent Switch Development

It may be attractive to operate the lifting coils for MAGLEV in the persistent mode. As a result, an activity should be initiated to develop reliable persistent switches for CICC configurations to assure availability of this component when needed.

Failure Survey & FMECA Development for Superconducting Magnets & Cryosystems

I. STATEMENT OF PROBLEM

There are many common features and operating modes among magnet systems, whether built for fusion confinement, high energy physics accelerators and detectors, power generation, energy storage, medical imaging, or MAGLEV systems. The history of magnet system accidents & failures can be of particular interest in assessing safety issues and, by studying common operational failure experience, to develop an approach to FMECA (Failure Modes Effects & Criticality Analysis) for magnets. This would lead to more reliable and fault tolerant designs for MAGLEV systems and components.

## II. BACKGROUND

In the early 1980's, a survey was distributed to laboratories in the USA which design, build and use magnet systems, and the results were analyzed. A summary was published [2.1] to help designers gain insight into critical areas. Of 31 incidents reported, only two indicated that the system could not be repaired. In 20 instances, incidents caused significant project schedule slippage, and in 7, a reduced operational rating was necessary. In 9 incidents, there was very little or no effect on schedule or operation. Although there were no resulting loss of life instances, it was clear that significant cost and schedule impacts were not unusual.

The survey also indicated that design error was the greatest single failure initiator, followed by improper assembly. The most common failure location was the coil winding. A subsequent survey has been performed for fusion magnet systems with somewhat similar results [2.2].

The value of these surveys is that they indicate areas where improved design is necessary and where extra attention must be given in magnet construction. Reliability and availability will be crucial to the success of MAGLEV. A comprehensive survey and analysis of events can help educate designers of MAGLEV magnet systems on likely areas of design and operational failure in the past to minimize the likelihood of repeating similar problems in the future. This can then contribute to a generic approach to FMECA for superconducting magnet systems which can then be used for improvements in reliability and availability.

## III. RECOMMENDED RESEARCH

### Literature Review & Survey

Perform a literature review of magnet system component failures and carry out a survey in the US & abroad to prepare/update a magnet and cryosystem failure data base. Perform analyses to determine likely causes of downtime events and their criticality. Review design or operational changes which were made (where appropriate) to gain insight into methods for improving reliability and availability of magnet systems.

### Critical Areas for Design and/or Component Research

Review the results of the previous task and recommend areas for design and component research which can have a significant impact on reliability and availability.

### Review and Modification of Standard FMECA Methodology

Review and modify methods for Failure Mode Effects and Criticality Analysis for application to MAGLEV magnet systems. Apply the techniques to one or more "straw man" systems. Review results in light of the failure survey and recommendations for component research.

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# LIGHT WEIGHT, HIGH FIELD, STABLE, SUPERCONDUCTING MAGNETS FOR ADVANCED TRANSPORTATION SYSTEMS

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## I. STATEMENT OF PROBLEM

Although the Guideway may be the most expensive component of a MAGLEV system, the importance of a suitable magnet system should not be underestimated. The reliability of operation of MAGLEV depends on the superconducting magnets performing to their specifications in a reliable manner (i.e., without training or quenching). Besides reliability the magnets should produce high field, be sufficiently stable to withstand reasonable perturbations, be light weight, be protected in the event of a quench, and be economical (although performance should outweigh cost). We propose to develop superconducting magnets that have these features.

Our magnet designs are based on internally cooled, cable-in-conduit superconductor with Polymer Matrix Composites (PMC) as the structural reinforcement. Although the initial work is with metallic superconductors such as NbTi, the processes being developed will be applicable to the High Temperature Ceramic Superconductors when they become suitable for magnet applications.

## II. BACKGROUND

Internally cooled, cable-in-conduit superconductors have exceptionally stable operation at very high current densities for exceeding those achievable with cryostabilized pool boiling conductors. Winding pack current densities of 10 $kA/cm^2$ possible in MJ-size magnets producing maximum fields of 8 T when cooled with supercritical He-I at 4.2 K. Even higher fields (11 T) are achievable with NbTi, if He-II at 1.8 K is used as the coolant. The remarkable stability of cable-in-conduit superconductor does not require large helium mass flow. Rather the high stability arises from both the large surface area in contact with helium and the large transient heat transfer caused by the helium flow induced by the normal zone. One must of course be careful in the design to provide a conduit with sufficient strength to handle the large pressure that arises in the event of a propagating normal zone or a quench. Another reason for the exceptional stability of internally cooled superconducting magnets is that any heat produced by motion and frictional heating of the turns is intercepted by the liquid helium before it reaches the superconductor.

The internally cooled conductor offers three other advantages that become more important as the size of the magnet system increases. Since the conduit can be fully insulated, high voltages that may arise during an unexpected quench can be provided for in a reliable manner. Thus, the protection problem is greatly eased compared with pool boiling designs. Internally cooled superconductors can also be epoxy impregnated, since the cooling will remain unaffected. This permits close coupling of the winding with the structural support and minimizes the motion of the turns. In fact, as we shall see below, the structure can be incorporated conveniently as distributed structure throughout the winding pack rather than as lumped structure of stainless steel. Small scale tests can be performed to verify that the stresses can be calculated correctly and then the particular design can be extrapolated to larger sizes with confidence. Thus, expensive prototype development and testing is avoided. The third favorable design feature is that a dewar is not required, since the helium is doubly contained by the conduit and potting. The pressurized helium cooling inside the conductor conduit is not disturbed by any vehicle motion as will be the helium bath in a dewar for pool boiling coils.

## III. DISCUSSIONS

In order to make the magnets as light in weight as possible, one needs to improve all three factors determining the weight of a magnet, namely, the winding pack size, the intrinsic weight of the conductor, and the weight of the structure. The high overall current density of cable-in-conduit superconductors ensures that the minimum amount of superconductor is used to produce the desired maximum field. This reduces the winding pack dimensions and hence, the weight. Furthermore it can be shown from first principles for solenoids that the mass of the winding pack per unit of stored energy varies inversely with the square of the field intensity. Thus the winding pack mass can be minimized by operating the superconductor near its practical field limit which for NbTi superconductor at a helium temperature of 4.2 K is 8 T.

The intrinsic conductor weight can be minimized by using Aluminum conduit instead of copper or stainless steel. Another feature of the compaction of the conduit is to have it drawn to a rectangular shape. This aids both in winding the conductor without incurring a twist and in obtaining the maximum packing factor of the winding.

The weight of the structure must be held to a minimum, which, according to the virial theorem, is proportional to the stored energy. The employment of PMC as structural support ensures minimum structural weight. This can be accomplished by either winding the PMC on the outside of the magnet as a lumped structure or preferably, by using the PMC in the form of a stocking over the conduit and thereby distributing the structure throughout the winding pack. It is also possible to use both techniques together. By using PMC as the structural containment in a completely potted design, it is possible and perhaps preferable to create a bobbinless magnet. This also helps to keep the weight to a minimum.

PMC as a structure also appears favorable for use with the High Temperature Ceramic Superconductors (HTCS). The high Young's modulus of the PMC structure (greater than stainless steel) along with higher tensile strength than stainless steel will be beneficial in minimizing the strain of the superconducting material, which does not possess high strain tolerance. It is also recognized that the protection of the HTCS will be a major problem in their application in high field magnets because of their high normal-state resistance. Because the thermal conductivity of PMC is larger than stainless steel, if it is distributed throughout a HTCS magnet, it will help spread out any joule heat produced during a quench and thus minimize the hot-spot temperature.

The only possible disadvantage to the type of magnet described above is the cryogenic system, which must employ parallel hydraulic connections with insulating breaks, if the conductor is to be operated in a series connection to the power system. However, techniques for making these connections are well known and require little development, since most resistive magnets are operated in this fashion with water-cooled, hollow conductor.

# CRYOGENIC REFRIGERATION FOR MAGLEV REQUIREMENTS AND OPPORTUNITIES

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# CRYOGENIC REFRIGERATION FOR MAGLEV

1. ENABLING TECHNOLOGY - FOR SUPERCONDUCTIVITY

   a. MECHANICAL REFRIGERATION
   b. ECONOMIC CRYOGENIC SYSTEM

2. CRYOGENIC SYSTEM

   a. HEAT LOADS

      CURRENT LEADS
      PERSISTANT MODE
      SUPPORTS - DEAD WEIGHT
      SUPPORTS - LIVE LOADS
      RADIATION SHIELDS - MLI
      MAGNETIC SHIELDS

   b. COOLING MECHANISM

      POOL BOILING
      CONVECTION - TWO PHASE
      CONVECTION - SINGLE PHASE LIQUID
      CONVECTION - COMPRESSED GAS
      CONDUCTION

SLIDE 1

# CRYOGENIC REFRIGERATION FOR MAGLEV

2. CRYOGENIC SYSTEM (CONT'D)

   c. DEWAR

      COLD PRESSURE VESSEL
      NO COLD PRESSURE VESSEL

   d. OPERATING TEMPERATURE

      LIQUID HELIUM
      SUPERFLUID HELIUM
      HTSC - 30 TO 50K

   e. REFRIGERATION SOURCE

      CRYOGENIC LIQUIDS - OPEN SYSTEM
      MECHANICAL REFRIGERATION - CLOSED SYSTEM
      COMBINATIONS

SLIDE 2

# CRYOGENIC REFRIGERATION FOR MAGLEV

3. DESIGN OPPORTUNITIES

   a. HEAT LOADS

      CURRENT LEADS VS. PERSISTENT MODE
      DYNAMIC LOADING - VIBRATIONS
      MAGNETIC DISTURBANCES
      SUSPENSION DYNAMICS
      PROPULSION REACTIONS
      EDDY CURRENTS

   b. MECHANICAL REFRIGERATION

      MAJOR ADVANCES NEEDED
      AVAILABLE SYSTEMS ARE LIMITING
      APPLICATIONS
      PAST PROGRESS VERY SLOW
      OPPORTUNITY COMPARABLE WITH HTSC

SLIDE 3

## CRYOGENIC REFRIGERATION FOR MAGLEV

4. WHAT WOULD PUSH-BUTTON HELIUM TEMPERATURE DO FOR SC APPLICATIONS?

   THE SAME AS THE COLLINS CRYOSTAT DID FOR LOW TEMPERATURE PHYSICS

SLIDE 4

# HE II AND MAGLEV - IS THERE A ROLE?

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## I. STATEMENT OF PROBLEM

**He II operation of superconducting magnets is reviewed to ascertain advantages or disabilities with MAGLEV use. The reduced temperature of operation results in increased critical currents such that the total amount of superconductor can be reduced, either by increasing the transport current and reducing the number of turns, or by reducing the area of superconductor and stabilizer for a constant transport current. Increased cooling reduces the amount of stabilizer necessary for cryostable operation, such that small stabilizer to superconductor ratios may not preclude cryostable operation. Transient He II cooling exists for larger times, compared to transient normal helium cooling, such that larger disturbances may exist in the magnet without affecting stability. However, the reduced operating temperature increases the refrigeration power input. A detailed system study needs to be performed and a compact He II refrigeration system needs to be designed to better assess the impact of He II cooling on MAGLEV superconducting magnet operation.**

## II. BACKGROUND

The history of MAGLEV development spans almost 25 years.[1,2] The US program lost funding in 1975, whereas progress continued in Germany, England, and Japan; with MAGLEV systems using superconducting magnets being developed in Japan since 1970. The performance of these superconducting magnets has significantly improved as superconducting technology has improved. Yamaji and Nakashima[3] summarized progress in MAGLEV superconducting magnet development:

1) Intrinsic stabilized epoxy-impregnated superconducting coils with high current density and high magnetomotive force.
2) Reduced weight and size with low heat leakage.
3) Small on-board refrigeration systems.
4) High resistance persistent current switches.

Improvements in superconducting magnets have resulted in smaller, lighter magnets that provide more magnetomotive force with higher current densities, inductance, stored energy, and maximum magnetic field in the coil. Initially magnets tended to be cryostable, but present magnets, with copper to superconductor ratios of one, tend to be intrinsically stable against conductor motion. In addition, improvements in cryogenic designs have reduced the heat leak. Further improvement in the superconducting magnet parameters may necessitate the use of new principles or materials, such as He II cooling.

Use of He II in superconducting magnets has been suggested for SMES[4] and Tokamaks[5]. These applications have prompted experimental research on He II, involving time dependent heat transfer and high heat flux thermal boundary resistance. Reviews, such as by Van Sciver,[5,6] have pointed out comparisons between normal helium cooling and superfluid helium cooling. The peak heat flux and recovery heat flux are larger for He II, but are also dependent upon the geometry of the cooling channels. Transient heat transfer is large and tends to be limited by Kapitza conductance and the thermal enthalpy of the helium in the coolant channel.

Implications of the use of He II in MAGLEV superconducting magnets are outlined in this paper. Operating at 1.8 K instead of 4.2 K means increased critical currents, but also increased refrigeration costs. He II cooling is larger than normal helium cooling, reducing the amount of stabilizer necessary for cryostable operation. Transient He II cooling may increase the stability of the magnet by handling larger disturbance energies. Each of these topics will be discussed in the following sections.

Critical Current - Amount of Superconductor

Operation of a superconducting magnet at a reduced temperature compared to 4.2 K results in an increase in the critical current of the superconductor.[5,7] The critical current as a function of magnet field may be described by

$$j_c = \alpha/(B + B_o)$$

where $B_o$ is about 1 T, and $\alpha$ is temperature dependent given by

$$\alpha = \alpha_o\{[1 - (T/T_c)^2]^2 - \beta T\}.$$

To a good approximation, this expression can be represented by a linear relationship

$$I = I_c(T_c - T)/(T_c - T_b).$$

These two expressions are graphed in Figure 1 for superconducting wire similar to that used in the background coil for the SMES proof-of-principle experiment,[8] to illustrate the increase in $I_c$ with reduced temperature operation. The critical current, in this example, increase by a factor of 1.5. This translates directly into a reduction of the amount of superconductor to 66% of the amount used at 4.2 K

He II Cooling - Amount of Stabilizer, Magnet Stability

Use of He II cooling results in increased peak nucleate boiling and recovery heat fluxes compared to normal helium pool boiling, see Figure 2. Peak nucleate boiling fluxes could be increased by factors of three, while recovery heat could be increased by an order of magnitude.

However, the peak nucleate boiling heat flux is dependent upon the geometry and path length to the heat exchange interface. The peak nucleate boiling heat flux is calculated from the temperature gradient in He II,

$$\text{grad } T = f(T)q^3,$$

where $f(T) = A\rho_n/S^4\rho s^3T^3$ is a function of temperature and pressure and has a value of about $0.67 \times 10^{-3}$ $cm^5K/W^3$ at 1.9 K. The quantity A is the Gorter-Mellink mutual friction parameter. The peak heat flux is

$$q^{*3} = Z(T_b)/L$$

where $Z(T_b)$ = integral of $f^{-1}(T)$ from the bath temperature to the subcooled temperature, in part due to the hydrostatic head, or the lambda point 2.17 K. Z(1.8K) is 400 $W^3/cm^5$ where the integral extends to the lambda point. Figure 3 shows the relationship between the critical length and the peak boiling flux, with values as high as 5 $W/cm^2$ for distances on the order of 3-4 centimeters.

The recovery heat flux appears to be correlated with the film boiling heat transfer coefficient. It has been postulated that in the film boiling regime recovery occurs when a critical temperature difference between the sample and heater is reached, described by

$$\Delta T = q_r/h_{fb}.$$

This critical temperature is 22 K for recovery data at 2.01 K. In some systems with high film boiling coefficients no recovery heat flux is observed because the recovery heat flux exceeds the peak heat flux.

Initial MAGLEV magnet systems were cryostable, however recent systems are not. For cryostable systems, the increased heat fluxes with He II cooling would reduce the amount of copper necessary. For present intrinsically stable conductors, He II cooling moves the conductor toward a cryogenically stable condition. This may make the magnets inherently stable without compromising the amount of copper or the copper to superconductor ratio for intrinsic stability. However, a detailed systems study needs to be performed to establish the actual stability state of the magnets.

Transient He II Cooling - Intrinsic Magnet Stability

Transient He II cooling consists of two phenomena; one is the time to the onset of film boiling, and the second is the heat transfer coefficient before film boiling begins.[6,9,10]

The time when film boiling begins is determined by the enthalpy of the helium and the heating rate. The thermal conductivity of He II is very large, such that to induce boiling one must raise the temperature of the helium bath to the lambda point. The time to film boiling is related to the penetration of heat into the helium, and is given by

$\Delta t^* = K/Q^4$ where $K = 3\rho c\Delta T_o Z(T_b)$, see Figure 4.

Depending upon the heat flux, He II cooling exists in almost a metastable state for as long as hundreds of seconds before film boiling begins. During this time, the rate of heating is given by the heat transfer coefficient, which is determined by Kapitza conductance. The Kapitza conductance is determined by measurement, and has the empirical form

$$q_k = a(T_s^n - T_b^n),$$

where a is 0.02 to 0.06 and n is between 2.5 and 4. Rewriting the heat transfer as $q_k = h_k \Delta T$ yields $h_k = 1.6 \times 10^4$ W/m$^2$K at $\Delta T = 2.5$ K. This value is similar to transient heat transfer in normal helium for conductor motion less than 100 $\mu$s in duration.[11] The difference is that He II heat transfer can exist for extended periods of time compared to times of transient heat transfer in normal helium.

For MAGLEV stability, He II transient cooling rates are similar to normal helium transient cooling rates. He II transient cooling can exist for longer times than normal helium, such that greater disturbance energies may exist in the magnet without affecting stability. The larger disturbance energies tolerated in He II cooling than can be tolerated with normal helium cooling may allow increased transport current, reduced amounts of stabilizer, or larger conductor motion.

Refrigeration

Operation at a reduced temperature compared to present MAGLEV systems will require larger refrigerators. Typical MAGLEV refrigeration values are 5 W at 4.4 K.[12] Power requirements for refrigeration is approximately proportional to the Carnot factor $(T_h - T_c)/T_c$. Estimates of real optimized refrigeration power requirements at 1.8 K are about three times that at 4.2 K.[4] However, refrigeration at 1.8 K may be minimized with effective shielding such that the total input power is only increased by approximately 30%.[13] Thus, operation of a MAGLEV superconducting magnet at 1.8 K would incur only a modest increase in refrigeration power, between 2 to 10 W above present systems.

## III. RECOMMENDED RESEARCH

Reduction in mass of the superconducting magnets and improvement in the stability of the magnet due to He II cooling is significant with only a modest penalty in increased refrigeration power. To fully evaluate the impact of He II cooling in MAGLEV vehicles, a complete system study and an in-depth magnet stability analysis should be performed. Magnet stability analysis includes evaluation of minimum propagating zones, minimum quench energy, Cu/SC optimization, conductor motion, adiabatic stabilization, cryogenic stability, transient cooling, and normal zone evolution. In addition, a compact He II refrigerator needs to be designed, built, and tested.

Evaluation of He II use in MAGLEV requires work in the above research areas. These efforts are prioritized on a scale of 1 to 3, with 1 having the highest priority, in Table 1:

Table 1. Prioritization of Research Efforts

| | | |
|---|---|---|
| MAGLEV systems study | 1 | Systems benefit of 1.8K operation needs to be determined. |
| Compact He II refrigerator | 1 | Increased refrigeration and weight need to be evaluated and quantified. |
| He II Cooling | 2 | Appreciable work for SMES exists |
| Magnet Stability Analysis | 3 | Complete magnet characterization of present systems is important. |

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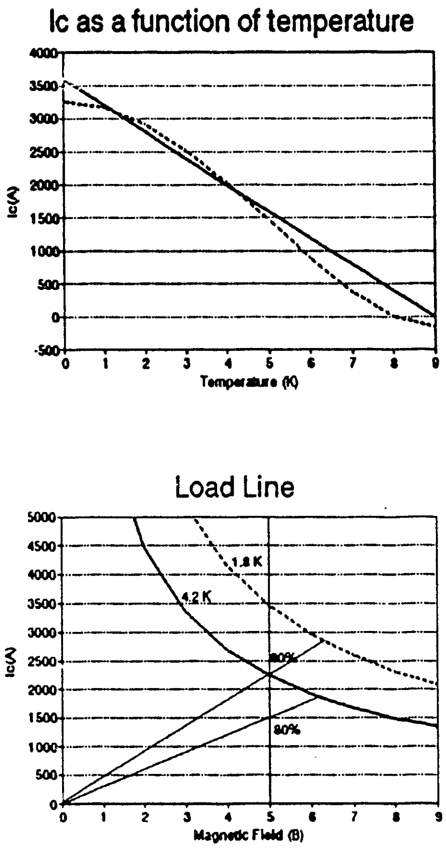


Figure 1, Critical current for superconducting wire similar to that used in the background coil for the SMES proof-of-principle experiment illustrating a factor of 1.5 increase with operation at 1.8 K compared to 4.2 K.

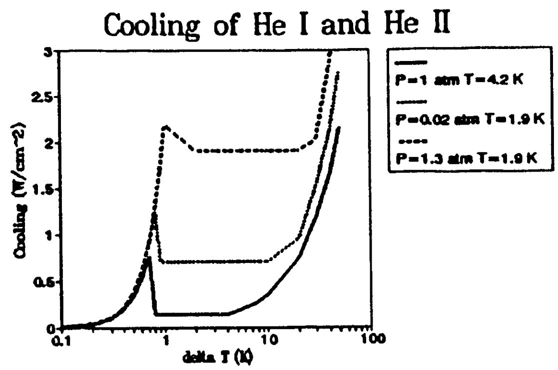


Figure 2, Typical heat transfer and boiling curve for He I and He II.[6]

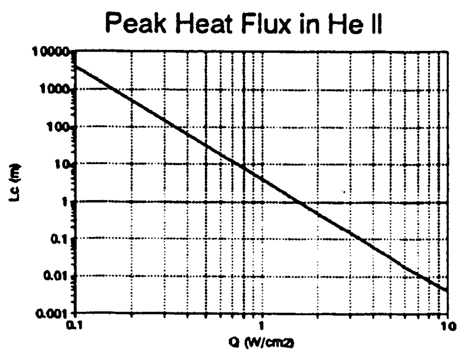


Figure 3, Critical length for linear heat flow.

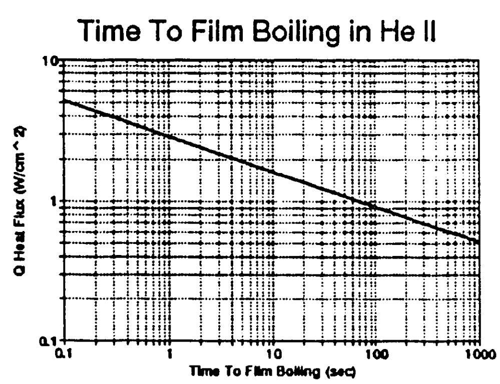


Figure 4, Time delay to film boiling.

## R&D NEEDS AND OPPORTUNITIES FOR APPLICATION OF SPACE VEHICLE CRYOGENIC TECHNOLOGY TO MAGLEV SYSTEMS

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## I. STATEMENT OF PROBLEM

### Magnet Stability

Magnet stability per se is fairly well understood for a variety of winding concepts and cooling schemes. What is not understood is the magnitude of expected disturbances for a given magnet design, and particularly for an individual magnet. This is especially true for maglev magnets, which are subjected to unique dynamic mechanical and electrical loads.

### Weight Reduction

Many trade-offs exist among components and operating parameters that lead to reduced weight. For example, aluminum stabilized conductor instead of copper, operating at 1.8 K instead of 4.3 K to achieve higher current densities in the NbTi, vapor cooled shields to reduce heat leak and refrigerator size, bucking coils instead of iron for shielding, etc. Advanced magnet protection schemes such as electromagnetic or thermohydraulic quenchback can be used to increase the overall current density and reduce the amount of required stabilizer, but accelerator dipoles are already manufactured with cable made from wire with a minimum amount of copper in it.

### On-board versus On-ground Cryogenic Systems

Both types exist for a variety of applications. Portable MRI units exist with on-board refrigerators. The Japanese have ~10 watts of refrigeration on-board MLU002, but reported contamination was a problem. On-ground systems are off the shelf technology, but cryogen transfer and on-board storage of liquid and boiloff gas must be dealt with. Presumably an on-ground system will be larger than on-board systems, which improves overall refrigeration efficiency. The real issue, though, is reliability. The weight of a ten watt refrigerator is minor compared to that of a maglev vehicle, as is the compressor power (~10 kW) compared to on-board hotel power.

### Advanced Helium Refrigeration (and Cryostats)

There is a widespread effort in this country and Japan to develop small, lightweight, long life cryocoolers with high efficiency and reliability. The Stirling cycle is a popular approach. Magnetic and gas bearings are the favored approach to long life and high reliability. Magnetic refrigeration operating on a Carnot cycle offers very high efficiencies at low temperatures, but will require a hybrid system for the top end. Operating designs do exist today, however. Several techniques are available to reduce heat leak to the cold mass. Accelerator magnets are advancing high strength, low conductivity support posts. Vapor cooled shields utilizing cryogen boiloff can greatly reduce heat leak. High temperature superconductors used in power leads can reduce heat leak, and have the potential to reflect all incoming infrared radiation when used as a thermal shield at 4 K.

## II. BACKGROUND

### Magnet Stability

There are two issues related to stability of maglev magnets which need to be resolved. The first is to determine the required current and stability margins necessary to operate a magnet that is *shaken* as hard and as long as a maglev magnet will be. This also means determining the best combination of conductor support and helium cooling. Do the windings look like an accelerator dipole? Should they be impregnated with epoxy and cooled indirectly? Is a cable-in-conduit conductor or a bath cooled conductor the best approach? What are the effects of vibration and fatigue on stability for different coil pack approaches?

The second issue related to stability is AC losses in the superconductor. What the dynamic loss limits in modern superconducts with ultra-fine filaments and cupro-nickel stabilized wire? Do superconducting maglev systems really need to be restricted to DC magnets?

### Weight Reduction

The information required here is simply a quantification of the benefits and trade-offs in terms of weight for the options available.

### On-Board versus On-Ground Cryogenic Systems

As stated previously, the real issue is reliability. Is it less probable to have a stranded vehicle half-way between stations because the on-board refrigerator failed or to have a vehicle stranded at a station because a cryogen resupply was unavailable? Will on-board systems reduce and isolate contamination problems? Will on-ground systems "infect" many trains with contaminated cryogens, or could a contaminated vehicle spread the "disease" to many on-ground systems?

### Advanced Helium Refrigeration (and Cryostats)

The problem with the small refrigerators being developed today is that they are not directed at maglev performance requirements. Maglev will require on the order of 10 watts of refrigeration at 4 K per 20 tons of vehicle. Cryocoolers are being targeted at perhaps 1 watt at 20 K. Thus design approaches being pursued need to be scaled up in capacity. Then data must be obtained for reliability, mean time between failure (MTBF), and efficiency over operational lifetimes for the scaled up designs.

For advanced cryostat designs, the question is whether they can be integrated into the maglev vehicle while retaining the advertised advantages of low heat leak. Composite supports are better than metallic ones in terms of fatigue, but cryogenic creep data is limited and more is needed. Vapor cooled shields require that one does something with the vapor: can the refrigeration system handle this requirement? Finally, there is some experimental data on heat leak of high $T_c$ leads operating between 80 K and 4 K, but how would these be integrated into the cryogenic system?

## III. RECOMMENDED RESEARCH

### Magnet Stability

The steps in a program to ascertain the design requirements for stability of maglev magnets are as follows:

1) Characterize the dynamic mechanical and electrical loads on conceptual designs of maglev superconducting magnets. These would be derived from conceptual studies of potential superconducting maglev systems which should include the possibility of AC superconducting magnets.

2) Perform trade studies and analyses to select a favored approach to assuring stability in a vibration and fatigue, time-varying current environment.

3) Build small model magnets that capture the support and cooling characteristics of the selected concepts. Operate them on shaker tables in a fashion that reproduces the mechanical and electrical loads seen on a vehicle.

4) Measure stability margin as a function of winding concept, current margin, load level, load frequency, and number of cycles. Drive out the design requirements and expected design margins for full scale magnets.

### Weight Reduction and Cryogenic System Type/Location

The thinking required to explore all the opportunities and system ramifications simply needs to be done. Support interested groups to develop conceptual designs of integrated maglev systems. Direct the design studies to look at: a) innovative ways to reduce weight on the vehicle; and b) innovative ways to cool the magnets. Continue support of promising approaches with follow-on detail design, development, and test of component hardware. At this stage performance benefits and system compatibility should be quantified by analysis and test.

### Advanced Helium Refrigeration (and Cryostats)

Characterize the heat loads, cryogenic system interfaces, compressor power availability, and reliability a maglev refrigerator must support. Support a hardware development program directed to these design requirements. Select promising options for bench tests of prototype machines and systems.

Verify long-term reliability and efficiency while operating in a simulated maglev environment. The simulated maglev environment must be derived from conceptual analyses of potential systems.

Concluding Remark

Several research opportunities exist to advance magnet and cryogenic hardware to the requirements of superconducting maglev. However, a starting point is needed. Conceptual design studies of maglev systems are needed to drive out hardware requirements. A coordinated effort to find the best maglev system for U.S. needs is necessary. This effort will be on the order of the programs being carried out by NASA to develop the space station, national aerospace plane, and next generation heavy lift launch system. It can be done and the U.S. knows how to do it. All it takes is a vision and a commitment.

# HIGH EFFICIENCY PROPULSION AND LEVITATION SYSTEMS*

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## I. STATEMENT OF PROBLEM

Why Maglev?

The benefits of maglev compared with other modes of travel are many. In an age of growing U.S. vulnerability to disruptions in oil supplies, Maglev offers a form of transportation powered by electricity, which is only 30 percent dependent on petroleum. What's more, maglev vehicles use only a quarter to half as much energy as jet aircraft and private automobiles.

They also have a relatively low environmental impact. They make less noise than any other system at the same speed; all observers of high-speed maglev test vehicles have commented that the noise is surprisingly modest. Similarly, the land required for maglev is less than for any other mode per unit of capacity. Although a 100-foot maglev right of way is only twice as wide as railway right of way, a "magway" can carry five times as many passengers per hour. And airports, though not directly comparable, are clearly more land-intensive than magways. The Dallas-Fort Worth Airport occupies 17,800 acres, enough land to create a maglev corridor 100 feet wide and 1,466 miles long. The new Denver airport will occupy comparable land-several times that of a magway with the same capacity based on average jet-travel distances.

Better still, building a magway need not cause massive environmental destruction. The French and English have found that many communities want a station on a high-speed train line but do not want the line to be built on new rights of way that slice their towns in half. Most of a U.S. maglev system could be built on existing interstate highway rights of way with negligible disruption.

Maglev also promises to be safer than any other mode of intercity travel. The closest comparable mode is high-speed rail. The passenger fatality rate for the Japanese Shinkansen and the French TGV is reportedly zero after billions of passenger miles of travel. For comparison, the fatality rates are 0.4 per billion passenger miles for intercity jet and bus and 10 for private automobiles. Light high-speed rail, maglev will use mostly elevated guideways that are unlikely to be encroached on, and it does not require on-board fuel, which can cause fatal fires in an accident. Similarly, it will have sophisticated automatic control systems, will receive frequent automated inspections, and will likely attract the most competent operational personnel.

Maglev can be even safer than high-speed rail if it is designed with less possibility of derailment, more automatic guideway sensing, and controls that are more resistant to human errors. And because the vehicle does not touch the guideway, accidents related to weather and wear will be minimized.

The initial capital cost of maglev need not be higher than the $8 million to $10 million per mile required for a TGV system or for new interstate highways, and the maintenance can be substantially less than the TGV cost of $2 to $3 per train mile. The higher speed still attract more riders, making the final system less expensive to the user than a slower high-speed rail system.

What's more, maglev vehicles could carry freight at rates competitive with trucks and with shipping times only a little longer than by air. Even if maglev shipping were more expensive than trucking, businesses would frequently pay a premium for speed. Witness the dramatic success of overnight courier service and the trend away from railways to highways for shipping in spite of the higher cost per tone-mile. Recognizing this trend, the Germans plan to carry freight on their new 155-mph Inter City Express rail system, and recent studies suggest that piggy back freight capabilities could dramatically improve the already strong economic advantages of maglev.

## II. BACKGROUND

### Why Repulsive Maglev is So Attractive

Of the two basic methods for providing levitation - electromagnetic suspensions (EMS) and electrodynamic suspension (EDS) - the latter appears to be more suitable for wide use. The drawback of EMS systems, which rely on attractive force, is the need to maintain a narrow air gap. This problem arises because EMS vehicles must use magnets with normal conductors, such as copper or aluminum, instead of superconductors. Attractive systems are unstable unless the current in the magnets can be varied widely and rapidly, as is possible with normal magnets. Without a way of controlling the current, the attractive force increases as the gap decreases, further narrowing the gap until, finally, it closes.

No maglev system that requires magnets with normal conducts can operate with an air gap greater than about three-eights of an inch without unacceptable power consumption, vehicle weight, and guideway cost. A wider gap might be feasible if an attractive system could use superconductors, but all known superconductors must operate with essentially constant current, and thus cannot be controlled in the way that is necessary to keep a stable gap.

In contrast, a repulsive, or electrodynamic suspension, system is inherently stable. The current induced in the guideway will increase as the gap shrinks, thereby increasing the repulsive force and providing steady suspension. Since the vehicle's magnetic field can be constant, it can be supplied by superconducting magnets, allowing a gap of two to six inches. As a result, EDS guideways do not require nearly the precise alignment or constant maintenance of EMS guideways.

No new technology is needed to make an EDS system practical: low-temperature superconductors are more than adequate for EDS systems, and reliable closed-cycle refrigeration equipment is now in everyday use. We simply need to design a system that uses existing technology in an optimal way.

Electrodynamic suspension does have its drawbacks. Systems built so are have been less efficient and have required more power than existing EMS designs. But this problem can be minimized by replacing the continuous sheets in the guideway with cleverly designed coils that use less current.

Another drawback is that because the magnetic fields on the vehicle are stronger than in an EMS system. more money and effort must go into shielding people from them, both inside and outside the vehicle. It is now believed that to avoid any health risk, the fields from a maglev suspension should be not much greater than the earth's magnetic field anywhere there are likely to be people. Neverthe less, the ability to use a wider gap, lower-cost guideways, lighter vehicles, and higher speeds would more than compensate for the added development cost for a practical EDS system.

## III. RECOMMENDED RESEARCH

### Switching and Stopping

A limitation of electrodynamic suspension - the preferred type of maglev for the United States - is that it cannot provide levitation at low speeds. This means that vehicles will need auxiliary suspension when they are switched off line for unloading and loading and when forced to stop between off-ramps.

For loading and unloading, the most widely accepted proposal is to use rubber-tired wheels. Like the MIT Magneplane design, vehicles could use wheels that extend laterally to engage an upward-sloping off-ramp. The integrity of the guideway is not broached by this scheme, as it is with the railroad-style guideway switch that is commonly proposed. To minimize the need for other traffic to slow down, a vehicle would exit and enter the guideway at 60 mph.

Providing for stops in an emergency is more complicated. Although a maglev vehicle traveling at 250 mph could easily come to a halt in a mile, getting it restarted would require special measures. It would be possible to have ramps for wheels running the length of the guideway, so the vehicle could roll until it reached a high enough speed for levitation. But this would be prohibitively expensive. If the power system did not fail, the linear synchronous motor could be programmed to provide enough lift to support the vehicle at low speed while stopping and restarting. If the power grid failed, however, emergency generators would be activated to allow all vehicles to travel at reduced speed to the next offramp. In an extreme worst case, the vehicle would "land" on the guideway and coast to a stop on disposable skids.

*Text taken in part from "Why the U.S. Needs a Maglev System", R.D. Thornton, Technology Review, April 1991.

# ACTIVE DAMPING OF MAGLEV VEHICLES USING SUPERCONDUCTING LINEAR SYNCHRONOUS MOTORS

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ABSTRACT

This paper explores the use of linear synchronous motor control to provide active damping for magnetically-levitated vehicles. Using a single LSM only heave and surge damping can be provided, but, with a dual LSM, roll and yaw damping can also be achieved. The paper gives design data applicable to the reference design of the P.S.M. 500 km/h Maglev system.

## I. STATEMENT OF PROBLEM

Several electrodynamically-levitated high-speed vehicle systems are currently under development in Japan, in West Germany and in the USA (See review (1)). Generally in these systems, levitation is achieved by the interaction of superconducting magnets on the moving vehicle with conducting strips or coils on the guideway while propulsion is achieved by a linear synchronous motor (LSM) consisting of superconducting magnets on the vehicle and current-carrying coils on the guideway. One of the characteristics of electrodynamically-levitated vehicles is the lack of inherent damping of many of the characteristic modes.

Earlier papers have introduced the concept of using the linear synchronous motor to provide active damping of heave and surge (2,3). This paper extends the application of active damping to include yaw and roll. Particular reference is made to the DOT/FRA Maglev design for a 500 km/h vehicle system (4). The magnitudes of the control forces and torques available in the four modes is discussed and a method of detecting heave and roll perturbations without vehicle sensors is presented.

## II. BACKGROUND

Most design for electrodynamically-levitated vehicles employ a single LSM for propulsion. For those with flat-topped guideways, lateral stabilization is provided by figure-eight type, null-flux coils on the guideway under the LSM stator winding. The dual-LSM system (5) shown in Figure 1 uses a different approach to vehicle guidance and provides for roll and yaw damping. In this system propulsion is provided by two linear synchronous motors each comprising an array of superconducting magnets on the vehicle and a three-phase stator winding on the guideway. No ferromagnetic material is employed on either the vehicle or the guideway.

sensors and communication channels. Yaw damping would, however, require such on-board equipment.

This active damping system is not considered to be complete in itself but to be combined with the active or passive mechanical damping of the levitation and propulsion magnet suspensions. The design approach is to achieve safety with the mechanical system and to supplement this by use of the LSM damping to achieve a highly acceptable ride quality.

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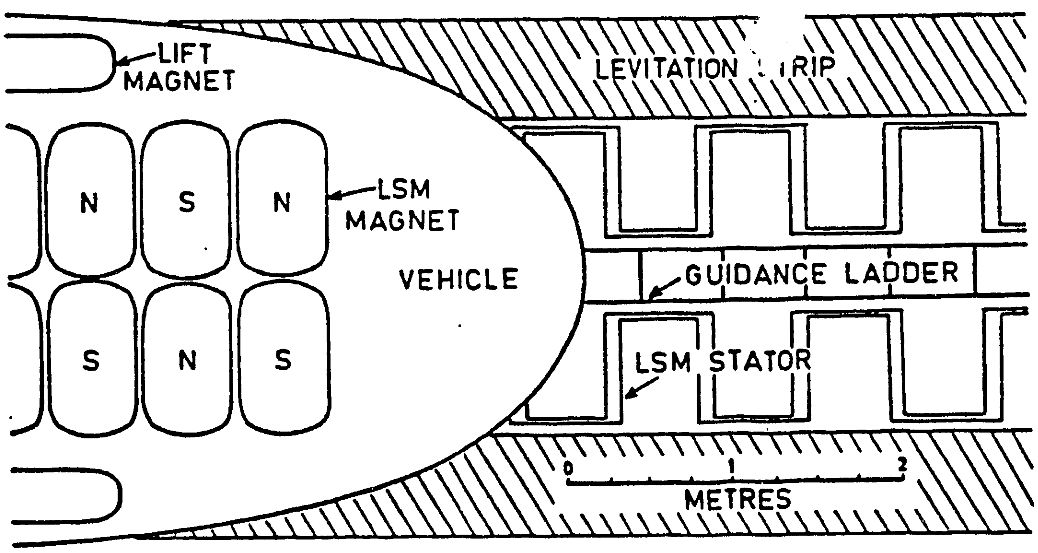


Figure 1. Dual Linear Synchronous Motor and Ladder Guidance System.

Table 1. Design Parameters for Single & Dual LSM Systems

| | Single | Dual |
|---|---|---|
| **Common Design Characteristics** | | |
| Thrust, kN* | | 40 |
| Cruising Speed, km/h | | 480 |
| Mechanical Power, MW* | | 5.33 |
| Motor Efficiency | | 0.75 |
| Stator Section Length, km | | 5 |
| Field-Stator Winding Separation, mm | | 220 |
| Field MMF of magnets, kA | | 500 |
| Total Magnetic Moment of Magnets, MA-$m^2$* | | 21.2 |
| **Magnets** | **Single** | **Dual** |
| Number of Full-Size Magnets | 49 | 35 |
| Mean Length, m | 0.53 | 0.74 |
| Mean Width, m | 1.7 | 0.9 |
| Wavelength, m | 1.14 | 1.56 |
| Self Inductance, H | 0.705 | 0.502 |
| MMF of Interpod Magnets, kA | 160 | 140 |
| Mean Length-of Interpod Magnets, m | 0.275 | 0.44 |
| **Stator Winding** | | |
| Parallel Conductors/Phase | 2 | 3 |
| Width, m | 1.6 | 0.625 |
| Lateral Offset of Winding re Magnet, m | 0 | -0.10 |
| Conductor Length/Phase/Guideway Length* | 7.61 | 10.8 |
| Winding Resistance ($R_s$), Ω/km | 0.521 | 0.105 |
| Leakage Inductance ($L_L$), mH/km | 2.36 | 0.89 |
| Mass of Aluminum Winding, kg/m* | 6.63 | 14.6 |
| **Guidance System** | | |
| Mass of Aluminum Winding, kg/m | 24 | 7.2 |
| **Operating Parameters** | | |
| Mutual Inductance ($M_{fs}$), μH | 17.65 | 6.98 |
| Heave Attenuation Factor ($K^1$) | 0.17 | 0.20 |
| Inverter Frequency, Hz | 117 | 85.5 |
| Phase Current, A | 476 | 750 |
| Phase Voltage, kV | 5.29 | 2.08 |
| Inverter Apparent Power, kVA* | 7.56 | 9.36 |
| Power Factor | 0.95 | 0.78 |

*Denotes values for two motors for the dual LSM.

# THE USE OF AC SUSPENSION MAGNETS FOR MAGLEV PROPULSION AND LEVITATION

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## I. STATEMENT OF PROBLEM

Analytical and experimental data exists for a variety of levitation and propulsion techniques for Maglev systems. The most advanced of the experimental systems are the German Transrapid and the Japanese MLU series.

### Transrapid

The Transrapid vehicle employs conventional copper coils for the attractive levitation magnets and for the field windings of a linear synchronous motor (LSM) for propulsion. The Transrapid exhibits a number of desirable system characteristics. The flat guideway should be simple to produce and relatively easy to install. The magnets used have an iron core and, together with the attractive rail, provide an essentially closed-flux path, making the stray magnetic field in the passenger compartment very low. The attractive system can levitate at slow or no speed without the necessity for a set of auxiliary retractable wheels, an important consideration for easy urban access. Finally, it should not be as susceptible to derailment as might be perceived for other systems, since the Transrapid vehicle wraps around the guideway.

The Transrapid also has its disadvantages. It uses standard copper windings, which are generally limited to current densities on the order of 300 Amps/cm$^2$, so the air gap between the magnet poles and the attractive rail on the underside of the guideway is limited to about 1 cm. This situation requires close-tolerance guideway alignment, and it raises concerns about the performance and safety effect of debris or ice build-up on the guideway. Additionally, the magnets on board the vehicle require continuous power to operate, and the task of supplying sufficient electrical power to the vehicle is complex.

### MLU

The Japanese MLU systems employ high-strength superconducting magnets for providing repulsive levitation through reaction with induced magnetic field in the guideway and to act as field windings for LSM propulsion. The benefits of the Japanese approach include reduced magnet power consumption (the on-board magnets operate in a persistent mode), significantly larger air gaps because high Ampere-turns are easily achievable with superconducting magnets, and a guideway which minimizes the possibility of derailment because of its "U" shape.

Among the disadvantages of the Japanese approach are a relatively intricate guideway cross-section (which may be more expensive to manufacture and install), and higher levels of stray magnetic field in the passenger compartment that require shielding, since the magnets have an air core. Also, as in any system which relies on induced eddy currents in the guideway to provide repulsive force, the vehicle can levitate only when a certain speed is achieved and must rely on auxiliary wheels at lower speeds.

It should be noted that both the Transrapid and the MLU Maglev systems employ LSM's for propulsion. The static field windings are on board the vehicle to react with a variable-frequency magnetic field supplied along the guideway. The cost of providing the active elements of the linear synchronous motor continuously throughout the guideway is quite high in comparison to an inactive guideway which is possible using linear induction motor (LIM) propulsion.

## II. BACKGROUND

In order to maximize the potential of Maglev it is necessary to meet the following system objectives concurrently:

1. The levitation system must be capable of performing safely at all speeds.
2. The stray magnetic field in the passenger compartment must be limited to a few gauss DC and a few milligauss AC.
3. The guideway cost must be minimized.
4. The on-board power requirements must be manageable.
5. The vehicle must be virtually incapable of derailment.
6. The air gap between the vehicle and the guideway must be adequate to provide for clearance under normal operating conditions and to minimize guideway installation and maintenance expense.

A combination of the best characteristics of the Transrapid and MLU systems provides an opportunity for meeting the above objectives concurrently. The application of innovative superconducting magnet technology has the potential for providing improvements in a hybrid system described below:

| | |
|---|---|
| Propulsion Method: | High Efficiency Superconducting Linear Induction Motor with Aluminum Eddy Current Sheet on the Guideway |
| Levitation Method: | Attractive Iron-Core Superconducting Magnet System with Iron Attraction Rail on the Guideway |

The benefits of this proposed system should be as follows:

1. The guideway cost would be minimized through the use of a superconducting LIM because it would contain only an inactive sheet of

aluminum rather than hundreds of active coils in each kilometer of guideway.

2. High flux densities could be maintained at larger air gaps due to the high Ampere-turns generated by the superconducting magnets. This would allow for larger, safer, more cost-effective clearances between the vehicle and the guideway.

3. The attractive levitation method would allow for a relatively simple, cost-effective, flat guideway shape. The system would be capable of levitation at any speed, including "zero". In addition, the iron-core levitation magnets and attractive rail in the guideway would form a flux path with minimal stray field leakage to the passenger compartment.

The problems which must be overcome in order to make the AC system viable form the basis for the research and development activities suggested in this paper.

## III. RECOMMENDED RESEARCH

Before AC superconducting levitation and propulsion magnets can be considered for incorporation into a Maglev system, there are a number of challenges which must be addressed. Among the most important are:

1. The magnets are AC superconducting devices and, hence, have losses. Are there materials available, or in development, which can meet the design requirements?

2. The superconducting LIM and the attractive levitation magnets require continuous power. Can a method be devised to transmit or store the necessary amounts of power on board the vehicle?

3. Can an effective superconducting LIM be designed? Can its high level of AC magnetic field be adequately shielded from the passenger compartment? Can its cryogenic refrigeration requirements be provided efficiently and economically?

4. Can an effective superconducting attractive levitation magnet be designed? Can its cryogenic refrigeration requirements be provided efficiently and economically?

5. On the basis of the research to be conducted, are the benefits of the proposed system realizable? Is the approach cost-effective?

At this time it is envisioned that the proposed system would utilize iron-core AC superconducting magnets to provide levitation and propulsion. The use of iron results in the following advantages to the magnet systems:

1. The peak field on the magnet windings can be kept quite low, which is a particularly important consideration in the design of magnets utilizing AC superconductors.

2. The propulsion and levitation forces are carried by the iron rather than being transmitted to the windings themselves, providing relief to the magnet's internal support structure.

The use of iron, therefore, simplifies the design and fabrication of the magnets and improves their cost, manufacturability and reliability.

The use of superconductor rather than copper windings results in the following advantages to the magnet system:

1. Power consumption is reduced because the superconducting windings have very small electrical resistance under AC conditions.

2. With a superconducting magnet's ability to produce very high current densities and, therefore, high Ampere-turns, the air gaps can be increased while maintaining the same operating flux density as with copper-wound devices operating at necessarily smaller air gaps.

As mentioned before, the AC system can become viable for Maglev only when a number of technical challenges have been overcome. Consequently, in descending order of priority, the following are recommended research topics:

Superconducting AC Materials

Superconducting magnets are generally considered to be DC devices because superconductor typically exhibits some hysteretic losses which limit key operating characteristics (i.e., critical field and critical current). Advanced, low-loss AC conductors have been designed, fabricated and utilized in successful experimental devices throughout the world, leading to the promise that it is possible to develop viable AC magnet systems for Maglev applications. Alternatively, it is possible that some of the evolving high temperature superconductors will prove to be useful materials in AC magnet applications.

Research efforts should be devoted to the identification and characterization of materials which are suitable for AC application. In addition, testing of samples should be conducted in order to categorize candidate conductors in environments as similar as possible to those of the proposed Maglev devices.

On-Board Power Supply

The propulsion and levitation magnet systems proposed are AC superconducting devices, which both require a continuous supply of power on board the vehicle. Although the use of superconducting windings will eliminate the need for power to overcome electrical resistance, the LIM (which dominates the power requirements) will still need reactive power and power to overcome the aerodynamic drag of the vehicle. At high speeds, this combined power requirement can reach is substantial. For an LIM to be a viable method of propulsion, a means of bringing large amounts of power on board the vehicle must be devised.

Research efforts should be devoted to developing a method by which significant amounts of electrical power can be brought on board the Maglev vehicle. Both contact and non-contact methods should be investigated.

Superconducting Linear Induction Motor

The propulsion system is a superconducting LIM on board the Maglev vehicle reacting with fields produced by eddy currents created in an aluminum sheet installed in the guideway. The advantages of using a superconducting LIM are:

1. It will not consume power to overcome electrical resistance in the windings, as is the case when standard copper windings are employed.

2. Since superconducting magnets are capable of producing much higher Ampere-turns than standard copper-wound magnets, a superconducting LIM should be able to operate with a larger air gap between it and the guideway.

While much analytical and experimental work has been done in the area of high speed LIM's, the use of a superconducting LIM has not yet been pursued. Although it is feasible to consider such a device, there are a number of problems which must be addressed and liquidated. Among them are:

1. Management of AC Hysteretic Losses
   Fields in the windings must be kept low in order to minimize AC losses, with the attendant reduction in achievable current densities and increases in cryogenic cooling requirements. Using an iron-core approach minimizes this problem.

2. Minimization of Support Structure and Maximization of Cryostat Efficiency for Low Refrigeration Requirements
   Once again, the iron-core approach improves this design aspect because the propulsive loads are transmitted to the iron and not to the windings themselves, thereby reducing the required magnet support structure.

3. Power Consumption
   The LIM requires substantial operating power. The use of superconductor will eliminate losses due to electrical resistance in the windings, and, since the high superconductor current densities will result in more compact coils, reactive power requirements should also be reduced. Vehicle aerodynamic drag will still require large propulsion power, however, and developing a means of supplying high levels of power on board the vehicle to the LIM represents an enabling technology.

4. Minimization of Stray Magnetic Fields in the Passenger Compartment
   The LIM is an AC device which would be operated in the proximity of the passenger compartment. Although the fact that it would be iron-core reduces the stray field, methods would have to be developed to reduce the stray field to acceptable limits.

Research efforts should be devoted to the conceptual design and characterization of such a device because of the potential it represents for significant guideway cost reduction.

Superconducting Attractive Magnet Systems

The proposed levitation system takes advantage of high-strength, iron-core AC superconducting magnets interacting with an iron attraction rail mounted on the underside of the guideway. This system has all of the desirable features of the Transrapid approach with the following addition benefits:

1. Due to the ability of the superconducting magnets to supply higher Ampere-turns, the air gap can be substantially increased beyond 1 cm, practically achievable using standard copper windings.

2. Because there is no electrical resistance in a superconductor, the power requirement is decreased.

Although this device has technical challenges similar to the superconducting LIM described above, it is somewhat less complex in that the magnet will operate in a DC mode with a relatively small, superimposed AC correction current. This is advantageous to the performance of the AC conductor since the hysteretic heating losses will be reduced.

Research efforts should be devoted to the conceptual design and characterization of the AC levitation magnet systems.

Cryogenic Cooling Systems

Special attention must be paid to the cryogenic cooling system because:

1. The magnets are AC and will have some level of hysteretic losses.

2. The magnets will operate in a powered mode with fixed current leads.

There are several ways to provide adequate cryogenic cooling to the magnet systems (for example, open-cycle reservoir, refrigerated, etc.), but the cooling system must be optimized to the particular requirements of a Maglev vehicle.

Research efforts should be devoted to the conceptual design and characterization of cryogenic cooling systems designed to interface effectively with the AC superconducting magnets and the Maglev vehicle.

# AN INTEGRATED APPROACH TO DEVELOP CONDUCTORS, COILS, CRYOGENIC SYSTEM, ON-BOARD MAGNET ASSEMBLY

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## I. STATEMENT OF PROBLEM

While considerable design information exists on superconducting maglev in terms of defining the configuration and ampere turns required, experimental data on operation of superconducting maglev systems is limited, and it is only the Japanese that have designed and operated complete superconductive assemblies in a maglev environment.

In the proposed Japanese high speed system one set of superconducting coils on the vehicle are used for levitation, propulsion and guidance. Levitation and guidance are achieved through discrete and separate levitation and guidance track coils in a null flux mode. Null flux meaning that the track currents are induced only if the vehicle is not at the no force central position.

When in motion, the levitation force is achieved when the vehicle is offset from the zero force central position and track currents are induced. The interaction of the magnetic field produced by the track currents with the superconducting coil on the vehicle produces the required levitating force - equal to the weight of the vehicle plus any additional vertical forces required for turns, dynamics, and vertical components of wind load.

## II. BACKGROUND

As described above, a levitation force is exerted directly on the superconducting coil windings. Transmission of this force to room temperature through low heat load structural members is required.

In a similar manner, propulsion and guidance forces are exerted directly on the superconductor.

While other proposed configurations differ in various degrees from the Japanese in air core configurations, forces are exerted directly on the conductor. Both steady and transient forces and magnetic fields result from the interaction of vehicle and discrete guideway coils. These are a major determinant of the heat load to the refrigeration system because of AC losses in the superconductor, eddy currents in metal cryostat walls, heat conducted in structural members designed to take vehicle weight plus the full range of dynamic forces.

Conductors and windings used so far were developed for operation in essentially a D.C. or slowly varying environment. They are nevertheless exposed to high loads and have to operate in time varying magnetic fields.

Conductors for the Superconducting Super collider have been developed that use 2.5 to 6 micron superconducting filaments. Because of the use of copper matrix, these are still primarily D.C. conductors. Even finer filament conductors with cupro-nickel matrices suitable for power frequency operation have been available in small quantities. These are considerably less sensitive to magnetic field changes than conductors designed for D.C. operation. Further, the windings themselves need to have enough precompression and probably need to be potted or impregnated to prevent conductor motion under any possible transients.

Metal cryostats have been used without fully taking into account the full range of forces, eddy current heating induced by track levitation, propulsion, and guidance currents.

Approach

In order to develop a compact, reliable, low heat load superconducting maglev vehicle magnet system, it is necessary to take an integrated approach to defining a design. For each potential major coil/track combination utilizing superconductors, the magnetic configuration, winding bundle, support structure, cryostat, and refrigeration should be iterated and compared among each other to achieve the required static and dynamic forces to levitate, guide and propel the vehicle under normal and emergency conditions within established constraints of weight, reliability, cost, and external magnetic fields.

Mobile Magnetic Resonance Imaging (MRI) presents an excellent analogy to developing superconducting maglev technology. This major superconducting application has achieved significant integration: high effective, compact thermal and structural design coupled with operation of a high current density superconducting persistent coil with active shield windings. In application, 1 meter diameter superconducting magnets are cooled down, put into a tractor trailer, energized, then moved as required from site to site - while still energized. Open cycle heat loads are a few tenths of a watt - meaning the system can be operated either open cycle or closed cycle with minimal refrigeration.

While MRI is essentially a D.C. application, the basic approach of designing for minimal heat load should allow consideration of not only open cycle and closed cycle refrigeration, but also a heat sink design in which heat is absorbed within the on board cryogenic system, then cooled periodically - at stations, at the end of the trip or at the end of the day.

The major difference in the maglev application is the larger time varying forces and magnetic fields expected. An integrated approach that minimizes heat generation due to superconductor AC losses, eddy current heating, conduction down power leads and structural components, and thermal radiation should result in an optimal superconducting system.

Because of the complex interaction of track currents with the vehicle superconducting maglev assembly and the integrated nature of the design, testing of full size coil assemblies including low heat load cryostats is an essential part of the development. This will identify any changes required early in the program.

## III. RECOMMENDED RESEARCH

### Conductor

High current density conductor is required that carries stable current for the specific load/magnetic field conditions expected. Conductor AC loss under worst case conditions should be less than or comparable to other heat loads under these conditions.

### Magnetic Fields/Forces of Vehicle Coil/Track Configuration

The magnetic fields and forces for each configuration need to be determined. Steady, quasi-steady, time varying normal and worst case conditions need to be computed.

Clearly, levitation using metallic sheet guideway is likely to have fewer higher frequency magnetic fields than discrete coils. Synchronous propulsion, which requires discrete guideway coils, is inherently a major source of undesirable time varying magnetic fields.

Dynamic effects due to vehicle motion need to be considered in determining the full range of characteristics.

### Thermally/Structurally Efficient Cryostat

Low heat load that considers the following:

1. Superinsulation
2. Multiple Thermal Shields
3. Eddy Current heating reduced to values less than other heat loads

   - use thin walled high electrical high resistance steel for helium vacuum vessel;

   - use non metallic helium temperature components.

4. Removable electrical leads and persistent mode operation.

5. Alternately, the use of High Tc superconductor power leads to minimize heat load.

6. Non-metallic high strength/low conductivity support structure for air core systems, the full magnetic forces act upon the conductor and must be transmitted to room temperature. This is not the same for iron core systems.

7. Unless required by system dynamics, minimize eddy currents in room temperature vacuum vessel.

   - non metallic
   - thin walled stainless steel
   - interrupt main eddy current paths (combination nonmetallic/metallic)

High Current Density Coil/Winding Configuration

Static and dynamic levitation, guidance, and propulsion forces on the superconducting coils need to be analyzed. The coil must then be designed to mechanically transmit these forces from the winding bundle to the winding support which in turn transmits this force to room temperature. Most coils used so far have an essentially rectangular configuration. Because forces on coils are perpendicular to the direction of current flow, levitation occurs on the sections of coil parallel to the direction of travel. In a similar manner, propulsion or braking can be achieved only on section of coil perpendicular to the direction of travel. The winding bundle must be sufficiently rigid mechanically or precompressed to transmit the steady and time varying loads without excessive conductor movement - a potential source of winding quench.

The correct combination of high current density conductor, mechanical, and cooling characteristics are an important aspect of achieving stable operation under all expected conditions.

# PARAMETRIC STUDIES OF SUSPENSION AND PROPULSION SUBSYSTEMS IN A MAGLEV TRANSPORTATION SYSTEM

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## I. STATEMENT OF PROBLEM

The required technology for developing a MAGLEV vehicle is very diverse. Our concentration will be on the concept development of propulsion and suspension subsystems.

There are two techniques for magnetic levitation. An electromagnetic suspension (EMS) method makes use of the forces between magnets, either permanent magnets or electromagnets. An electrodynamic suspension (EDS) method relies on the forces between a magnetic-field source and the eddy currents induced by it in a conducting track. There are many candidate propulsion methods. Linear synchronous motors (LSM) and linear induction motors (LIM) are two examples. There are many ways to apply the suspension methods and to configure the propulsion subsystems. As of today, there are sparse design studies and prototypes. However, there is no clear evidence as to which combination is the best. The decision on which combination to be preferred should come from a detailed trade-off study among the system performance, economic conditions, environmental impact, etc.

## II. BACKGROUND

Before embarking on an expensive program of prototype development and testing, it is desirable to carry out a trade-off study of the system or subsystem performance on certain parameters. For a suspension subsystem or a propulsion subsystem, the study should be focused on the dependence of power requirement and force generation on gap width, magnets or sources arrangements, and track material properties, etc. There exist many reports describing studies, some of which include test data. It will be beneficial to collect all these reports and summarize the data for easy reference.

The parameter space for the suspension and propulsion subsystems is generally very large. Thus, one should not expect that existing studies have fully addressed the dependence of the system or subsystem performance on all the important parameter values. For this reason, it will be extremely valuable to have analytical models and corresponding computer codes capable of addressing the roles of all these parameters. The availability of such models and computer codes is essential for identifying innovative design alternatives. They can also provide valuable inputs for the design of feedback control systems required for vehicle smoothness or passenger safety and comfort.

III. RECOMMENDED RESEARCH

To provide additional information required for a detailed trade-off study, two research areas are recommended:

a. reviewing existing analysis and test data (priority 2),

b. developing and applying analytical models and computer codes for quantifying subsystem performance and identifying promising design alternatives (priority 1).

Technical approaches for the two recommended research areas follow.

a. Review of Existing Analysis and Test Data

There are many MAGLEV related articles in open literatures, such as IEEE journals, industrial reports and government documents. They cover almost all areas of MAGLEV vehicles. The review effort will focus on the areas related to the suspension and propulsion subsystems. Special emphasis will be on the various prototypes developed in Germany, Japan, Canada and the United States. For the articles reporting analytical and experimental results, the first step in the review will be to determine the soundness of the analysis and experiment, to identify their limitations or deficiencies, and to suggest methods for improvement. For the results judged to be sound, our next step is to assess the advantages and disadvantages of the performance of the studied concept. The issues on cost and the environmental impact of stray magnetic fields will also be included in the assessment process. Review articles are also available on some prototype systems. The pros and cons of various prototype systems will also be addressed.

b. Development and Application of Analytical Models and Computer Codes for Quantifying Subsystem Performance and Identifying Promising Design Alternatives

There are many design alternatives for the propulsion and suspension subsystems of a MAGLEV vehicle. To carry out a separate analysis for every possible alternative is tedious and often not desirable. We recommend that a general generic problem be analyzed so that many design alternatives can be investigated by simply changing some parameter values.

The general generic problem we recommend to solve is a four layered boundary-value problem. The four layered structure is used to model a very general suspension or propulsion subsystem, or a combined propulsion and suspension subsystem. In the four layered structure arranged sequentially, layers 1 and 4 are taken to be non-conducting, either free space or infinitely laminated iron, layer 3 is free space, and layer 2 is the reactive track having constant uniaxial conductivity and permeability. The uniaxial track parameters are used to approximate various track configurations, such as discrete rods, or finitely laminated iron. The magnetic-field sources, either current loops or magnet poles, are taken to be at the interface of layers 3 and 4, or at the interface of layers 2 and 3, r at both interfaces. That is, layer 4 and the source at the interface of layers 3 and 4 are to simulate the vehicle, while layers 1 and 2 and any possible source at the interface of layers 2 and 3 are to simulate the guideway, or vice versa. By taking different source arrangements, both LIM and LSM propulsion methods can be analyzed. By using different materials for the layers, both repulsive and attractive (or electromagnetic and electrodynamic) suspension methods can be studied.

We will apply Maxwell's equations in a moving medium together with Fourier transforms to solve the boundary-value problem. The use of Fourier transform will enable us to consider the problem in the wave-number space (e.g., $k_x$, $k_y$), thus simplifying the equations to be solved considerably. All the performance characteristics will be explicitly formulated in terms of integrals. These integrals, although expected to be complicated, will not cause great concern when numerical techniques are used for performing the integrations. However, it is desirable to have some quick physical insights before resorting to complicated numerical calculations. If we neglect the spatial variations transverse to the guideway, meaningful approximations to the integrals can be obtained. It is expected that such a two-dimensional approximation will not introduce too much errors for most performance characteristics. One important exception is the lateral force which will arise when certain non-symmetrical transverse variations occur. Such three-dimensional phenomenon will also introduce some reduction in the suspension and propulsion forces. These three dimensional corrections will also be treated.

The above procedure will give us general formulations for the propulsion (or drag) and suspension forces, the power factors, and the efficiencies as a function of vehicle and guideway parameters. These parameters will include relative velocity, the source frequency, and the arrangement parameters such as the lengths and separations of magnet poles and current loops, and the thickness, conductivity, and permeability of the reactive track. The formulas will be computer-coded. The computer codes will be used to generate results to compare with available data.

With the analytical model and the computer codes in place, two design alternatives will be studied in detail, namely, (1) a combined propulsion and suspension subsystem and (2) a combined suspension subsystem using both permanent magnets and electromagnets.

b.1 A Combined Propulsion and Suspension Subsystem

The subsystem to be considered here involves using a linear induction motor for propulsion. The question is whether or not such a subsystem can also provide enough suspension forces with proper source and reactive track arrangements. We are aware that the Rohr Industries, Inc., has employed such a subsystem to develop a prototype. That particular prototype uses highly laminated iron, while the reactive track has a high permeability to provide the attractive suspension force and a non-zero conductivity in the transverse direction (provided by discrete aluminum bars) for the propulsion force. We will carry out a detailed performance analysis for a subsystem of this type, using source frequency, velocity, current winding arrangements, gap width, aluminum-bar size and spacing, etc., as parameters. From the analysis, its feasibility will be assessed and the required parameter values will be identified.

### b.2 A Combined Suspension Subsystem Using Both Permanent Magnets and Electromagnets

The reason for using such a combined approach is to maintain a smooth ride when irregularities arise along the guideway. When irregularities arise, this approach will allow for a feedback control design to change the strength of the electromagnets so that a bumpy ride would not occur. The purpose of this study is to provide inputs for determining the required amounts of changes in electromagnet strength as a function of the guideway irregularities. The irregularities can be, e.g., grade and curvature changes or the swing of the vehicle by a strong wind. Making use of the analytical models and computer codes described earlier, we will perform a detailed analysis to obtain the dependence of various force components on gap width, lateral displacement, pole dimensions and strengths of the magnets. Such information will be required not only for the feedback control design to maintain smooth rides, but also in the beginning phase of the subsystem design for determining the allocation of the permanent magnets and electromagnets. The end result of this analysis will be the identification of the required parameter values for feasibility assessment.

# INTEGRATED MAGLEV R&D TESTING REQUIREMENTS

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(SLIDES)

# COMPUTER CODE DEVELOPMENT

MODIFICATIONS AND IMPROVEMENTS

- o SECONDARY SUSPENSIONS
- o ARBITRARY NUMBER OF MAGNETS
- o CURVED GUIDEWAYS, SLOPES
- o GUIDEWAY DEFLECTIONS AND DYNAMIC INTERACTIONS
- o IMPROVED INPUT/OUTPUT SCREENS
- o GENERALIZED PROPULSION INPUTS

GIVE TO INDUSTRY TO PROMOTE INTEREST USE TO ANALYZE EXPERIMENTAL DATA

SLIDE 1

## EXPERIMENTAL FACILITY PRELIMINARY DESIGN

POWER

- o TWO 1.5 MW VARIABLE FREQUENCY VARIABLE VOLTAGE (GTO THYRISTOR), SYNCHRONIZATION CAPABILITY
- o PROVISION FOR POWER PICK-UP

PROPULSION

- o CHANGEABLE TO SUIT SUSPENSION CONFIGURATION
- o PRESUMED LSM, PROVISION FOR LIM
- o PROVISIONS FOR DIFFERENT BLOCK LENGTHS

CONTROL FACILITY

- o CENTRAL CONTROL AND DATA ACQUISITION/PROCESSING

SLIDE 2

## RESEARCH AND DEVELOPMENT

VEHICLE

- o SUSPENSION - CONFIGURATION
- o FORCE VS DISPLACEMENT CHARACTERISTICS
- o CONTROL REQUIREMENTS 7 PASSENGER COMFORT
- o DAMPING REQUIREMENTS
- o SECONDARY SUSPENSIONS, ACTIVE PASSIVE
- o ACTIVE CONTROL
- o TOLERANCE OF GUIDEWAY IRREGULARITIES
- o TOLERANCE OF GUIDEWAY DYNAMIC MODES
- o POWER REQUIREMENTS
- o FAILURE MODES
- o COMMUNICATION/CONTROL REQUIREMENTS
- o SWITCHING CHARACTERISTICS/REQUIREMENTS
- o ENVIRONMENTAL EFFECTS: INTERIOR/EXTERIOR
- o MAINTAINABILITY

APPROACH: INCORPORATE TECHNOLOGY IN VEHICLE TO MINIMIZE COST OF GUIDEWAY

SLIDE 3

# RESEARCH AND DEVELOPMENT

GUIDEWAY:

| | |
|---|---|
| CONSTRUCTION: | FABRICATION (PREFAB)/TRANSPORT/INSTALLATION STRESSES, NORMAL AND BRAKING LOADS |
| MATERIALS: | STRENGTH/RIGIDITY/MAINTAINABILITY-LIFETIME MAGNETIC INTERACTIONS |
| TEMPERATURE: | THERMAL STRESS & STRAIN |
| TOLERANCES: | CONSTRUCTION/INSTALLATION/ MAINTENANCE |
| GROUND MOTION: | SEISMIC DISTURBANCES/SETTLING OF FOUNDATION |
| ARCHITECTURE: | ASTHETICS, COMPATIBILITY WITH FUNCTIONS |
| ENVIRONMENT: | LAND USE/VISUAL, NOISE, EM SHIELDING |
| SAFETY: | FENCING/OBSTACLE DETECTION |
| AUXILIARY USES: | FIBER OPTICS? |

SLIDE 4

# RESEARCH AND DEVELOPMENT

GUIDEWAY-VEHICLE:

| | |
|---|---|
| STATIC INTERACTIONS | o GUIDEWAY DEFLECTION/RIGIDITY |
| DYNAMIC INTERACTION | o GUIDEWAY MODES STIMULATED BY VEHICLE |
| | o MULTIPLE VEHICLE EFFECTS |
| | o VEHICLE MODES STIMULATED BY GUIDEWAY |
| | o MOTOR/PROPULSION VARIATIONS |
| | o PASSENGER COMFORT |
| SWITCHING | o METHODS/REQUIREMENTS |
| HILLS, TUNNELS | o REQUIREMENTS |
| GUIDEWAY-PROPULSION | o MEANS OF INSTALLING/MAINTAINING |
| | o CHEMICAL INTERACTIONS - ALUMINUM-CONCRETE |
| | o POWER PICK-UP |
| | o POWER DISTRIBUTION/SECURITY |

SLIDE 5

# EXPERIMENTAL FACILITY PRELIMINARY DESIGN

VEHICLE

- o 7.4 M LONG, 1.7 M WIDE, 1.7 M HIGH, 3 METRIC TONS
- o 10 - 20 kW ON BOARD POWER
- o COMPLETE DYNAMIC INSTRUMENTATION, TELEMETRY
- o TEST CELL FOR COMPONENTS, SUBSYSTEMS
- o PROVISIONS FOR MOUNTING PRIMARY AND SECONDARY SUSPENSION SYSTEMS
- o RETRACTABLE AIRCRAFT TYPE WHEELS FOR LOW SPEED SUSPENSION OF EDS SYSTEMS AND COMPONENT TESTING
- o 150 MPH (67 m/s) DESIGN SPEED, 0.2 G ACCELERATION

SLIDE 6

**RESEARCH REQUIREMENTS DETERMINE THE SIZE OF THE TEST FACILITY**

TRADEOFF - VEHICLE TECHNOLOGY VS GUIDEWAY COST

- o SUSPENSION COMPLEXITY VS GDWY TOLERANCE
- o GUIDEWAY RIGIDITY VS PASSENGER COMFORT

EVALUATE LARGER MORE COMPLEX DESIGNS

- o SUSPENSION INTERFERENCE WITH CYLINDER
- o COMPLEX SUSPENSION INTERACTION WITH GDWY
- o RIDE QUALITY
- o INTERACTION OF SUBSYSTEMS
- o HILLS, CURVES, TUNNELS, SWITCHES
- o VEHICLE, PROPULSION, CONTROL SYSTEMS
- o COMPUTER SIMULATION VALIDATIONS
- o COMMON BASIS COMPARISON OF SUSPENSIONS

SYSTEM SAFETY EVALUATIONS

- o EMERGENCY BRAKING, EM, AERO, MECHANICAL
- o FAILURE MODES

SLIDE 7

# EXPERIMENTAL FACILITY PRELIMINARY DESIGN

GUIDEWAY

- o ELEVATED, TWO MILES LONG, BEAM AND PIER, INSTRUMENTED
- o FIRST AND LAST THIRD FOR ACCELERATION/DECELERATION
- o CENTRAL THIRD MODIFIABLE FOR EXPERIMENTATION
- o PROVISION FOR FUTURE CURVE, SWITCH, HILL
- o TWO METERS WIDE, DOUBLE TEE DESIGN
- o TESTING OF WIDE VARIETY OF SUSPENSION CONCEPTS

SLIDE 8

# THE IMPACT OF RIGHT-OF-WAY GEOMETRY ON RIDE QUALITY

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## I. STATEMENT OF PROBLEM

A tenet of the rebirth of Maglev technology in the United States is the promise of the free use of rights-of-way already amortized for other transportation modes. The requirement to purchase land for new rights-of-way would increase the Maglev implementation cost by several fold and, in all likelihood, would doom the realization of this new, and promising technology. Existing rights-of-way worth considering are exemplified by the Interstate Highway System and existing conventional rail lines. Senator Moynihan (D-NY) has proposed dual-use of the Interstate Highways, and many of today's Maglev investigations are concentrating on this concept.

This immediately raises a critical consideration for Maglev designers and those planning for their implementation. Existing highways and rail lines were originally designed for travel well under 100 mph and the curves and grades were planned for this relatively low speed service. We now must find ways to accommodate a vehicle traveling at three to five times the original planned speed.

Fortunately, we are still in the design phase and there seems to be no inherent reason why we cannot design a Maglev vehicle to negotiate almost any chosen alignment. We cannot, however, avoid the laws of Newtonian mechanics, and the passengers will be subjected to centripetal loads and other accelerations determined by the guideway geometry and vehicle speed. The questions which arise are; how fast can we travel over existing routes, what will be the impact on passenger comfort, and to what extent must the alignments be modified to achieve a reasonable balance between comfort and speed?

## II. BACKGROUND

In our recently completed study of Maglev applications in New York State (Ref. 1), we conducted a preliminary analysis of maglev alignments along the New York State Thruway. A very simplified approach to ride comfort was adopted, in that we set certain acceleration levels which were not to be exceeded. In particular, we limited the vertical acceleration to 1.1 g. We further assumed that the vehicle and/or guideway would be banked at an appropriate angle such that coordinated turns would be performed, i.e. there would be no lateral accelerations in the turns. This is essentially how an airplane flies. This leads to a maximum bank angle of 24.6°. At this bank angle the achievable speed is related to the turn radius as follows:

$$V(\text{mph}) = 2.581\sqrt{\text{turn radius(ft)}} \qquad (1)$$

Typical alignment geometry data for the NYS Thruway is shown in Fig. 1. This data was analyzed using the above simplified analysis and the results are shown in Fig. 2. This analysis shows that even in a fairly twisty portion of the Thruway, average speeds approaching 250 mph are possible. Unfortunately, this simplified analysis ignores several important factors involved in ride quality, and a more rigorous analysis is required before a final answer is known.

The Pepler criterion (Ref. 2) has been specified for the route analysis required by the recently proposed Concept Definition Study to be contracted by the Federal Railroad Administration. This ride comfort analysis technique was derived from observational data on bus and train experiments. It resulted in a numerical comfort criterion which depends on the roll rate (Wr), the ambient noise level (dBa), the transverse acceleration ($a_t$), and the vertical acceleration ($a_v$). The Pepler equation is given by equation 2.

$$C = 1 + .5Wr + .1 \text{ (dBa -65)} + 17a_t + 17_v \quad (2)$$

The corresponding comfort levels are as follows:

| | | | |
|---|---|---|---|
| C=1: | Very Comfortable | C=4: | Neutral |
| C=2: | Comfortable | C=5: | Somewhat Uncomfortable |
| C=3: | Somewhat Comfortablw | C=6: | Uncomfortable |

Although we cannot be certain how well these bus- and train-derived relationships will apply to Maglev vehicles, it does provide a convenient method of analysis to investigate the relationships of guideway contours and vehicle speed. One method of analysis would be to specify a particular comfort level which is not to be exceeded over a particular route. Each route segment could then be analyzed to find the speed which would yield that comfort level. The result would be a plot of average route speed versus comfort level.

Tangent sections (straightaways) would be analyzed by determining the dynamic oscillations and wind noise levels as a function of speed. In a coordinated turn the comfort index is increased due to the vertical component of acceleration. As an example, for the 24° banked turn, $a_v = .1$ and the comfort index increases by up to 1.7. We can immediately see the difficulty in achieving comfort levels better than "somewhat comfortable". In the transitions between tangents and curves we must roll up to bank angles of as much as 24°. A roll rate of 10°/sec will increase the comfort index by five and throw us into an uncomfortable condition. Even at this rate, the 2.4 sec to perform the roll maneuver will require 1000 ft of guideway at full speed and, as Fig. 1 shows, we do not always have that much space between turns. Certainly back-to-back turns in opposite directions will require much reduced speeds.

## III. RECOMMENDED RESEARCH

Two clear research needs exist. One is to develop the analytical methods to optimize the guideway centerline path for a particular given right-of-way. The independent variables would be the right-of-way contours and width and the details of the existing highway or track clearances. The guideway path could be restricted to one side or the medium, or it could be allowed to cross over in order to increase it's bend radius. It would also be permitted to leave the right-of-way to negotiate sharp bends if desired. The goal should be to develop an automated technique (because the data base might be quite large) which could optimize on some parameter of interest such as average route speed, ride quality, or the cost of land acquisition out of the designated right-of-way.

Development of such a technique would permit the rapid screening of candidate Maglev routes and would assist in the development of design requirements for Maglev vehicles.

The second research need is to investigate new ride quality criterion specifically developed for Maglev vehicles. We propose that this problem may be attacked with the use of aircraft flight simulators. A number of sophisticated simulation facilities exist around the country and they appear to have all of the attributes necessary to provide high fidelity simulations of Maglev performance.

Flight simulators may be divided into fixed base and motion base units. The fixed base simulators provide an accurate visual and sound representation but without motion. In many cases the physiological interactions desired are provided by the fixed base units. A more accurate representation is provided by the motion base simulators which provide accelerations in several degrees of freedom. An important consideration is that present-day scene generation is digital, and the software has a good probability of being either directly applicable or adaptable with some modification.

Ground level scene software is used for low level aircraft and helicopter simulations. Present scene generation software can be used at Maglev-relevant speeds at altitudes of say 25 ft. This software is usually easily modified to add features such as trees or buildings to improve the simulation realism at reasonable cost.

Simulators usually employ cockpit mockups in which pilots may "fly" the simulator. For Maglev simulations, it would be necessary to construct a passenger cabin with seats and windows but there would be no need for interactive control. Although one or two seats might be provided, there would be no need to simulate the whole passenger cabin because the motion and visual interactions of concern should be individual in nature.

A suggested program would be to subject a variety of untrained passengers to Maglev-relevant simulations and attempt to develop a new comfort criterion which would then be used to investigate candidate routes and guide maglev designers. These simulations could be performed at reasonable cost and would avoid the possibility of constructing a high cost demonstration system prior to proving that the passengers can tolerate the ride.

## IV. REFERENCES


1. Grumman Corp., Final Report, "New York State Technical and Economic Mag-lev Evaluation", The New York State Energy Research and Development Authority, to be published.

2. Dunlap and Associates, "Development of Techniques and Data for Evaluating Ride Quality", Vol. II, "Ride Quality Research", USDOT Transportation Systems Center, February, 1978.


# TYPICAL R.O.W. DATA

## (NYS THRUWAY)

**Table 6-3 NYS Thruway Data – Vicinity of Interchange 15 (Sheet 2 of 2)**

| Milepost | Radius, ft | Length, ft | Average row width, ft | Subtended angle, deg |
|---|---|---|---|---|
| MP 38.6 | 5000 | 500 | 270 | 5.73 |
| | Tangent | 600 | 290 | – |
| | 5000 | 500 | 270 | 5.73 |
| | 6500 | 2800 | [illegible] | 24.7 |
| | Tangent | 1400 | [illegible] | – |
| | 15000 | 2500 | 340 | 9.55 |
| | 10000 | 1700 | 290 | 9.74 |
| | Tangent | 1800 | 300 | – |
| | 9000 | 1100 | 300 | 7.0 |
| | 7000 | 1000 | 380 | 8.18 |
| MP 41.57 | Tangent | 2500 | 380 | – |
| | 30000 | 1200 | 330 | 4.0 |
| | 5600 | 700 | 290 | 7.16 |
| | 7000 | 700 | 200 | 5.73 |
| | Tangent | 3800 | 290 | – |
| | 5000 | 1500 | 300 | 17.2 |
| | 7600 | 500 | 340 | [illegible] |
| | Tangent | 1900 | 340 | – |
| MP 44.0 | 8000 | 2700 | 350 | 19.3 |
| | 25000 | 2400 | 340 | 5.5 |
| | 10000 | 880 | 250 | 5.0 |
| | 6000 | 750 | 340 | 7.16 |
| Int 16-45.2 | Tangent | 1600 | 290 | – |

# SPEED PROFILES

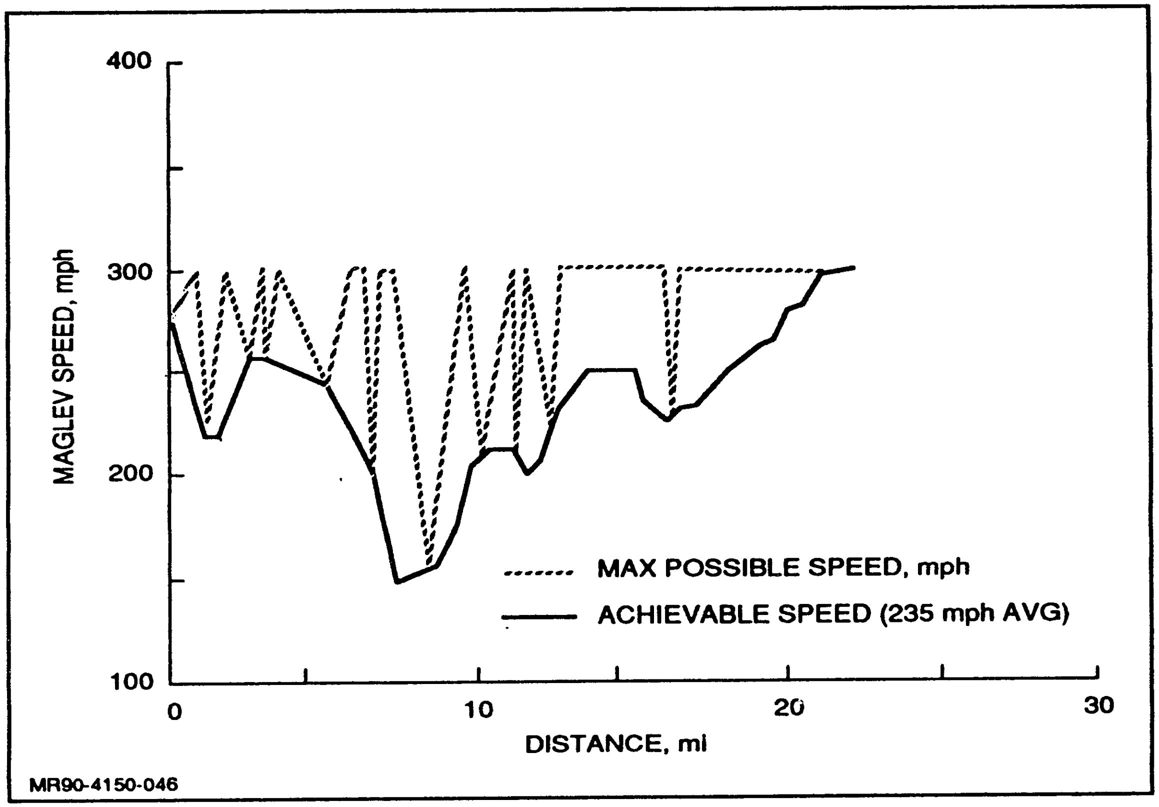


**Fig. 6-9 NYS Thruway MAGLEV Speed Profiles – Vicinity of Interchange 15**

# NEED FOR THE DETECTION OF GUIDEWAY MISALIGNMENT AND FOREIGN OBJECTS


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## I. STATEMENT OF PROBLEM

The presence of foreign objects on Maglev guideways, by accident or intentionally, or the misalignment of these guideways due to ground shifting or earthquakes represent major safety hazards to a Maglev vehicle. Contact of a Maglev vehicle traveling at 200 to 300 mph with even a small object (especially metallic) can result in severe damage to the vehicle. Misalignment in the guideway may cause derailment of the vehicle with catastrophic effect on the passengers and the surrounding area. An important need exist to provide a cost effective system that can continuously detect foreign objects and guideway misalignment/damage over its full length, with the minimum occurrence of false alarms. The need for such a detection system was recognized back in the 1960's and 70's when the Office of High Speed Ground Transportation (OHSGT) (subsequently the Federal Railroad Administration) tested two alternate systems designed for this purpose with limited success. Since this need still exist, with no obvious solution available, it is recommended that a new program be undertaken to satisfy this requirement.

## II. BACKGROUND

A brief history of the work that was performed by OHSGT (Ref. 1) during the late 60's and early 70's is given below:

In 1967, OHSGT surveyed potential obstacle detection techniques and selected and optical laser beam on which to start research.

The RCA Research Center developed a wayside scanning system using lasers. Although performance of the prototype on field tests was excellent, the cost of the scanner proved to be prohibitive. General Applied Science Laboratories (GASL) did further work on scanning and non-scanning lasers with the unexpected finding that laser beams projected over concrete pavement at the height of a few inches (75-100 mm) are bent upwards on hot days, thus missing the receiver and become inoperative. GASL then investigated electrostatic devices. These were dropped from the study when a new technique, a near-infrared beam produced from a diode, was demonstrated to the FRA by Applied Metro Technology (AMT) in July 1970. The cost of the diode was much lower than lasers and the beam was not subjected to thermal bending. AMT later marketed the technology as a burglar alarm system. This was the first non-transportation application spin-off of OHSGT technology.

Approximately 500 ft (152.4 m) of the Tracked Levitated Research Vehicle (TLRV) guideway at Pueblo was instrumented with miniature near-infrared transmitters located 25 ft (7.6 m) apart along the edge of the guideway. Receivers 50 ft (15.2 m) apart detected the beams. The transmitters were sequentially turned on (ripple-fired) and the central station monitored the transmitted signals. After installation in 1973, the system worked satisfactorily for a period of two months, i.e., obstacles were detected with an acceptable false-alarm rate. Then two types of unexpected failures occurred: ambient sunlight caused high false-alarm rates, and the optical filters became pockmarked. AMT was unable to correct the deficiencies so the concept was dropped from study.

## III. RECOMMENDED RESEARCH

The best way to avoid damage to the vehicle due to obstacle present on the guideway is to minimize the probability of obstacle occurrence. If the occurrence is infrequent then the need to perform repeated shut-down or slow-down of the system is minimized. Safety precautions to be taken to minimize this probability include:

- Construct elevated guideways 30-40 ft above the right-of-way and 16 ft above the crossovers.
- Construct cover/deflection screens over the guideway in areas where vandalism or sabotage is likely to occur.
- Provide guideway pitching for obstacles to roll off/away from critical sections of the guideway.
- Design for a wide range of environmental effects including: extreme temperature changes, ground shifting, earthquakes, and other natural phenomenon.

No matter how effectively the safety precautions identified above are implemented, they will not eliminate the need for a guideway safety detection system. They only minimize the number of system shut-downs or slow-downs that result. A need therefore exists to provide a cost effective system that can continuously detect foreign objects and guideway damage, with minimum false alarms. No known system seems to exist that can perform this function.

An apparent, cost effective, approach for solving the detection problem is to locate a scanning radar like system on each vehicle that continuously monitors the forward vehicle direction on the guideway. However, the need to look around curves and provide sufficient lead time of impending danger is not possible with such a system. The need therefore exists to 1) revisit the systems previously tested for the latest state-of-the-art developments, and 2) examine new obstacle and damage detection system for this application. Examples of systems that should be investigated include:

- IR diodes
- Radar on the guideways
- Fiber optics and other smart sensor systems
- Electrostatic detectors

- Lasers
- Sound waves

A preliminary set of requirements for a cost effective system that can continuously detect foreign objects and guideway misalignment/damage is presented in attachment 1. It is recommended that a study and test program of the latest sensor/smart structure technology be undertaken to identify the sensor, or combination of sensor systems, that can best meet the requirements identified above.

## IV. REFERENCE


1. Report on the 10th High Speed Ground Transportation Act of 1965, by the Secretary of Transportation to the President, the Senate and house of Representatives, PB 271508, FRA/ORD-77/27, May 1977.


### Attachment 1

### OBSTACLE AND GUIDEWAY DAMAGE DETECTOR SYSTEM REQUIREMENTS

1) DETECTION CAPABILITY

- DETECT OBSTACLE MATERIAL SUCH AS, METALS, WOOD, PLASTIC, ETC THAT:
  1) EXCEED 1 CUBIC INCH (16.4 CUBIC CM) IN SIZE
  2) ESTIMATE SIZE, WEIGHT AND MATERIAL TYPE*

- DETECT DISPLACEMENT OR FAILURE OF GUIDEWAY STRUCTURE THAT EXCEEDS (TBD) CM IN ANY DIRECTION

2) OPERATING REQUIREMENTS

- OPERATE UNDER A WIDE RANGE OF TEMPERATURE CONDITIONS (-20 DEG F TO +150 DEG F)

- NOT BE EFFECTED BY OR RESULT IN A SIGNIFICANT NUMBER OF FALSE ALARMS DUE TO:

  - WIND (UP TO 70 MPH), GUSTS (UP TO 100 MPH), RAIN (UP TO 2 IN/HR), SNOW (UP TO 1 IN/HR) AND FOG (WITH 5 FT VISIBILITY)

  - ANY DIRECT OR INDIRECT REFLECTIONS, OR GLINT FROM SUNLIGHT OR BRIGHT STREET LIGHTS

  - RISING HEAT WAVES FROM THE GUIDEWAY

  - NOISE DUE TO AUTO, AIRPLANE, OR OTHER SURROUNDING NOISE SOURCES

- DESIGN FOR LONG LIFE (> 5 YEARS), LOW FALSE ALARMS (< 1 FA/100 GUIDEWAY MILES/YR),.HIGH RELIABILITY, AND EASE OF MAINTAINABILITY

- LOW COST (<$200K/MILE)

* THIS REQUIREMENT SHALL BE A DESIGN GOAL

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## I. STATEMENT OF PROBLEM

Existing information on Maglev System Safety issues can be found in the following sources:

1. Safety of High Speed Magnetic Levitation Transportation Systems Preliminary Safety Review of the Transrapid Maglev System, R.M. Dorer and W.T. Hathaway, John A. Volpe National Transportation Systems Center Cambridge, MA DOT/FRA/ORD-90/09, November 1990.

2. Final Report of the New York State Technical & Economic Maglev Evaluation (in Draft Form), Grumman Space and Electronics Division in conjunction with Parsons Brinckerhoff Quade & Douglas, Inc., General Electric Company, Intermagnetics General Corporation, Brookhaven National Laboratory, prepared for NYSERDA, March 1991.

3. Civil Aspects of Maglev Design, Jan H. Zicha, P. E., De Leuw, Cather & Company.

4. Birmingham Airport Maglev-the Development and Design of the Support Structure and Guideway, B. H. North, FICE, FiStructE, FIHT, Director, The Henderson Busby Partnership, Ware, UK.

5. A Track Switch for Magnetically Levitated Vehicles, M.J. Lilley, BSc, MIEE, Senior Principal Scientific Officer, British Railways Board, Derby, UK.

6. The Magnetically Levitated Transport System TRANSRAPID Characteristics and Aspects of Application, Manfred Wackers.

7. Thermal Deformations in Typical Maglev Guideway Structures, T.I. Campbell and S.W. Siu, Journal of Advanced Transportation, Vol. 21, Winter, 1988.

8. Guideway for Maglev, Y. Sato, A. Matsuura and S. Miura, Quarterly Reports, Vol. 27, No. 2, 1986.

9. Plan and Execution of URT Construction Method, S. Takeshita, Quarterly Reports, Vol. 27, No. 2, 1986.

10. Test Laying of Roadbed across Structure Joint, S. Abe, K. Ando, and K. Shimbor, Quarterly Reports, Vol. 27, No. 2, 1986.

11. Development of an Electronic Rail Profilometer Referenced to Rail Baseplate and Measurements Using It, M. Katayamo, N. Abe, M. Satoch, and T. Sugiyama, Quarterly Reports, Vol. 27, No. 2, 1986.

12. Dynamic Interaction Between Propulsion and Suspension System in a Maglev Vehicle, E. Masada, K. Fujisaki, K. Hayafune, S. Suzuki and M. Kawashima.

## II. BACKGROUND

The information required to clarify issues of system safety have been divided into relevant subject areas. These are as follows:

Banking/Superelevation:

Investigations must take place to determine if airplane and train banking/superelevation are applicable to a Maglev vehicle. Also, it is not clear at this time if passengers will accept trips with many banks at 24 degrees along with a strong visual reference to ground level.

Switching:

Taking into account the speed and nature of the guideway, it is necessary to provide safe switching for the Maglev system.

Automatic Train Controls/Manual Override:

It is known that automatic train control will work on Automated People Movers in airports at low speeds. However, it must be determined if it will work on a Maglev system at high speeds.

On-Board Fire/Emergency Shut Down/Evacuation:

It is important to determine the most efficient and safest method of evacuating people from the Maglev system in the case of an on board emergency. That the guideway may be in an isolated area, distance from population centers, is a serious consideration.

Vehicle Interiors/Cabin Pressure/Window Glazing:

Within the interior of the Maglev vehicle, it is unknown what impacts traveling at high speeds will have on the passengers. Also, because the vehicle will travel at high speeds, it will be necessary to use a special, unspecified type of window glazing to prevent cracking from impacts with foreign objects.

Guideway Design and Construction Standards:

Guideway design and construction standards have been accomplished for viaducts, elevated highways, and elevated trains. However, it must be researched how these standards will differ for a Maglev system. This is a critical factor, primarily because the guideway construction makes up 70-90 percent of the Maglev system cost.

Emergency Braking/Loss of Power/Propulsion/Levitation/Guidance:

The best method of emergency stopping for the Maglev vehicle has not been determined yet and must be investigated.

Guideway Integrity/Obstacles on Track:

Obstacles on the Maglev track create a potentially dangerous situation due to the high speeds and inability for the vehicle to make abrupt stops. A means of detection must be determined for the system.

Electrical/Magnetic Field Shielding/Health Risks:

Electrical/Magnetic fields may create a health hazard to passengers and those in areas surrounding the Maglev system. It is necessary to investigate the effects these electrical and magnetic field rays will have on passengers and others once a Maglev system is in normal operation.

Aerodynamic Forces:

Aerodynamic forces exist within the Maglev system. Considering the cost of horizontal spaces and construction, as well as Right-of-Way limitations, the minimum safe passing distance between trains in opposing directions must be determined.

All Weather Conditions/High Winds/Earthquakes/Geological Conditions:

It is critical that the system operated safely in all weather conditions. Investigations to prevent and prepare for disastrous weather conditions are crucial.

Operator/Staff Training:

Qualified and trained personnel are a critical factor in safely operating and maintaining the Maglev system. Because there are no training programs for the Maglev systems, it is necessary to create a specialized training program.

Guideway Separation from Other Uses:

Investigations must be implemented to determine if guideway separation is safe on a highway median or if it requires its own right-of-way. The effects of other vehicles, such as trucks, cars, or trains, adjacent to the guideway must also be analyzed.

## III. RECOMMENDED RESEARCH

These same subject areas provide a basis to categorize recommended areas for future research.

Banking/Superelevation:

It is suggested that a variety of types of potential passengers, such as men, women, children, and elderly, should be tested using a flight simulator.

This method would help to analyze the tolerance different passengers may have to variations in banking curves.

Switching:

Research must be conducted to analyze complexities of switching at high speeds in relation to switching at low speeds.

Automatic Train Controls/Manual Override:

Testing of automatic train control could be researched in a full scale demonstration on a test track. The test track must be long enough to sufficiently allow operation at full speed for a significant distance.

On Board Fire/Emergency Shut Down/Evacuation:

Prevention of fires on board the Maglev vehicle should be studied, as well as emergency evacuation procedures in case of fire. This may also involve researching use of non-flammable materials.

Vehicle Interiors/Cabin Pressure/Window Glazing:

Analyzing the visual effects of speed on test subjects in simulated situations is a recommended method of determining the effects of Maglev speed on passengers.

Guideway Design and Construction Standards:

Testing of materials and stress situations such as those found in a Maglev guideway design should be researched. A test track will also serve as a research tool.

Emergency Braking/Loss of Power/Propulsion/Levitation/Guidance:

Investigation of skid systems and other secondary braking systems will help to determine the best emergency braking options.

Guideway Integrity/Obstacles on Track:

Research of detection systems to be placed along the guideway would benefit in early identification of obstacles on the Maglev track. The detection system must be automatic because of the vehicle operator will have insufficient reaction time to stop the vehicle. Existing electronic monitoring systems must be analyzed to determine effectiveness or new systems must be designed.

Electrical/Magnetic Field Shielding/Health Risks:

Magnetic and electrical rays testing and analysis are critical. The research of health risks on passengers, employees, and others in the surrounding areas due to the Maglev system is of vital importance.

Aerodynamic Forces:

Methods of investigative techniques on aerodynamic forces include simulated testing and computer scale testing.

All Weather Conditions/High Winds/Earthquakes/Geological Conditions:

Weather conditions can be researched using simulator testing methods and computer models to analyze the effects of different weather situations on the Maglev system.

Operator/Staff Training:

An effective training program must be created for Maglev system operating personnel. It is necessary to initially enroll all potential Maglev personnel in an extensive training program and to continuously reevaluate and retrain those personnel throughout the course of their employment.

Guideway Separation From Other Uses:

A test track will be useful in acquiring test data to determine the safest distance required for passing cars should be provided to avoid conflict with the Maglev system.

# SUSTAINED PASSENGER G-LOADS IN MAGLEV: NEEDS AND PAYOFFS

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## I. STATEMENT OF PROBLEM

The worldwide interest in high speed Maglev ground transportation is leading toward detailed engineering development of Maglev as a complete system. These studies in turn are bringing to light the important effects that many key parameters have both on the system design configuration, and on the costs to construct and maintain that system.

The purpose of this short paper is to highlight one area in which some straightforward research could pay large dividends in the near-term for Maglev route layouts now being evaluated. This research can include a fresh review and analysis of existing data as well as new work in specific areas.

The acceptable levels of sustained g-limits for Maglev passengers has a direct relationship to allowable combinations of speed and turn radius. This is true for both horizontal and vertical curves, and is well-known to transportation engineers. For the very high ground speeds of Maglev (500 + kph or 300 mph, even before considering evacuated tube systems), the resulting curve radii can be several kilometers, using present sustained horizontal and vertical g-levels commonly found in high speed rail and similar types of ground transport.

## II. BACKGROUND

It can be shown through the simple mathematics of the problem that relatively small increases in the allowable sustained g-loads in the vehicle can yield meaningful decreases in curve radii (or increases in speed with given radii).

Figure 1 shows the orientation of the vehicle axis system with a total vehicle bank angle $\theta$. This angle is the sum of guideway superelevation angle and additional vehicle tilt via a tilting suspension system. Guideway superelevation could be limited to the 10 to 12 deg range in order to permit both safe operation at low speeds and emergency evacuation from a stopped vehicle, so this type of suspension will be required to achieve total bank angles in the 20 to 25 deg range envirsioned for high speed operation.

The relationship between the global and vehicle reference system is:

$$\begin{bmatrix} x_v \\ y_v \end{bmatrix} = R_{ov} \begin{bmatrix} x_o \\ y_o \end{bmatrix} \quad (1)$$

where

$$R_{ov} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \qquad (2)$$

(rotation matrix from "O" to "V")

Using Figure 2 it is easy to express the g-loads on a banked vehicle in, for example, a horizontal turn:

$$[f_v] = R_{ov}\,[f_o] \qquad (3a)$$

or $$\begin{bmatrix} f^{vert} \\ f^{lat} \end{bmatrix}_v = R_{ov} \begin{bmatrix} 1.0 \\ v^2/rg \end{bmatrix} \qquad (3b)$$

; v = velocity, r = curve radius

Equations (3) and (4) express the relations between $f_v$, v, r and $\theta$. In other words, allowable g-forces, speed, radius and total bank angle can be traded off with each other to best meet system objectives. In the real situation, this would be done for all combinations of horizontal and vertical curve, as well as for all transitions in which rates of acceleration change ($\dot{a}$, or "jerk") are minimized.

As an example, past studies using 0.08g (lateral*) and 1.1g (vertical*) show that even with an ideal total vehicle bank angle of about 21 deg (at which these two g-limits are achieved simultaneously), the required horizontal curve radius is over 4 km at 500 kph (300 mph) speeds. This is shown in Figure 3. Factoring in transition sections it is, therefore, evident that the very large curve radii required for high speed Maglev will limit the flexibility of the route alignment or could cause operating speeds to be reduced. The accommodation of Maglev in existing interstate highway rights-of-way or the penetration of heavily developed metro corridors may not then be practical or cost-effective.

Figure 4 shows the example case another way, in which the total bank angle is shown as a function of turn radius for various speeds. For smaller bank angles the lateral limit (vehicle reference) of 0.08g is reached first, whereas above 21 deg or so the vertical limit of 1.10g controls. Note that further bank angles are incapable of reducing the horizontal curve radius unless the constituents of the allowable g-limit vector ($f_v$) are increased.

## III. RECOMMENDED RESEARCH

Using a similar example with 400 mph (179 m/sec), we can show that for small increases in the tolerable g-level, significant reductions in curve radius will result:

*in the vehicle reference system

| | Original g-limit | Example of Incrased Limit | Change |
|---|---|---|---|
| Lateral | 0.08g | 0.10g | +0.02g |
| Vertical | 1.10g | 1.15g | +0.05g |
| Min Turn Radius | 7+ km | 5 km | -2+ km (30% reduction) |

Therefore, a thorough investigation of tolerable sustained g-level is warranted since small increases in commonly acceptable levels could produce large benefits in improved route flexibility and lower costs. This can be accomplished along the following fronts:

A modern review of existing data from high speed rail, aircraft and NASA to form the core of a pertinent data base, which will certainly have to be augmented by new studies.

Simulator studies to establish acceptable comfort for sustained g-level can provide a valuable supplement to existing data. The simulation must be capable of applying sustained lateral and vertical g for at least several seconds if not more. Airline type (multi-axis motion) simulators cannot fully apply sustained g for this length of time since they rely on a combination of cab motion and orientation to provide the normal transient simulation of flight. Rather, the conditions here require only modest g-level over longer periods, pointing toward a centrifuge-type or flying aircraft-type simulation.

Also, these studies must include not only the effects on seated passenger, but also on passengers and crew in aisles, those with carry-ons, and possible meal service, etc. If follows that a full vehicle cross section (four abreast with aisle) with a usable cabin length would provide the most meaningful data.

A large centrifuge type setup could be practical and would have the advantage of potentially accommodating any appropriate vibratory inputs which could alter the tolerable sustained levels. (A separate study to review the appropriateness of the Peplar ride criteria would also be welcome, but is outside the scope of this paper.)

Another practical simulation could be done in an actual aircraft such as a narrow-body 707 or 727-type aircraft configured inside like an in-service Maglev vehicle. For many years, a modified KC-135 (707) has been used in the space program to simulate complete weightlessness for periods approaching 30 sec and so it would be easy to develop appropriate flight profiles to simulate a range of practical g-load vectors for the human factors study.

The bottom line is that since there might be a good change that sustained g-levels could be modestly increased (toward levels commonly accepted in commercial aircraft), and that these increases would pay off with significantly more practical and cost-effective route layouts, that this should be substantiated as soon as possible. New test tracks, commercial Maglev lines (in Japan and U.S.), and applications to existing ROWs such as the NYS Thruway are now under detailed consideration.

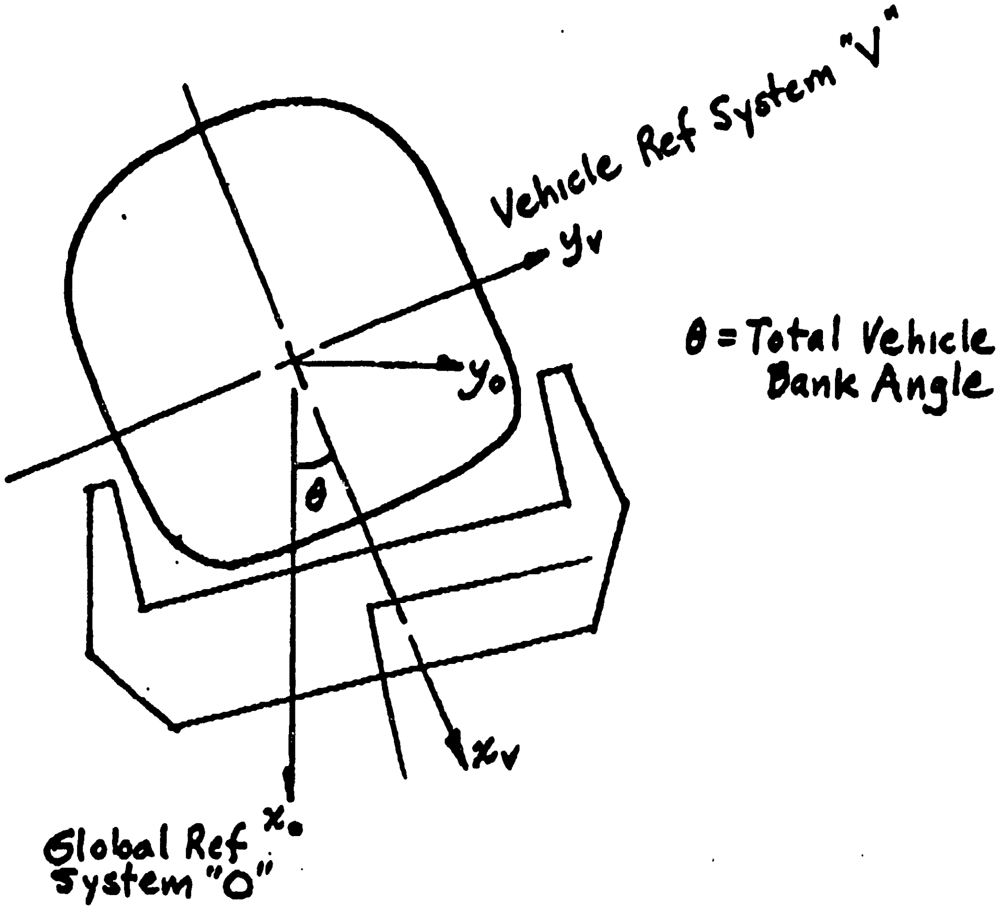



Figure 1. Banked Vehicle Reference System

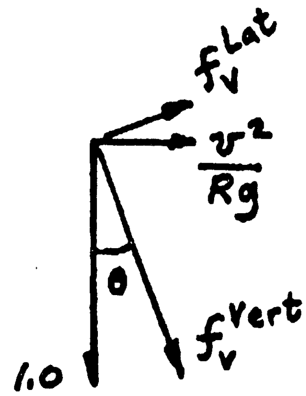
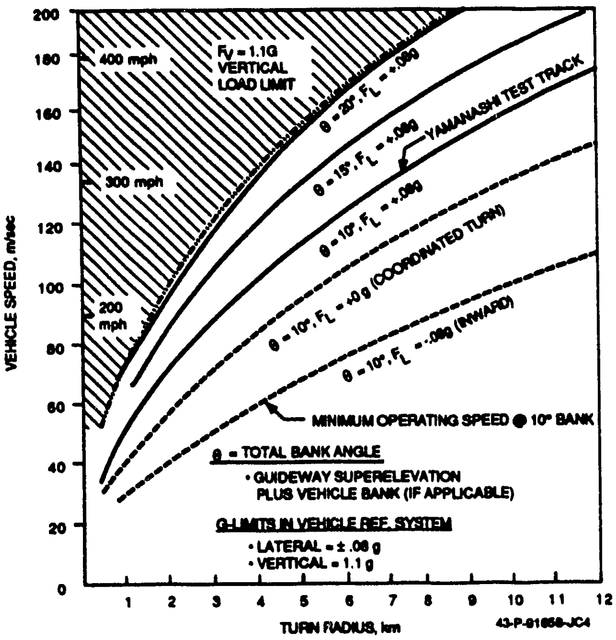



Figure 2. G-Loads in Vehicle Reference System for Horizontal Curve

# MINIMUM CURVE RADIUS FOR MAGLEV SUSTAINED - G LIMITS




## Example

**For +1.1 G vertical and + 0.08 G horizontal:**

**300 mph → R > 4 km**
**400 mph → R > 7 km**

**If 1.10 → 1.15 G vertical and +0.08 → 0.10 G horizontal,**

**Then $R_{min}$ decreases from 7+ to 5 km at 400 mph, or a 30 percent reduction**

Figure 3. Example of Minimum Horizontal Curve Radius versus Speed for Various Bank Angles

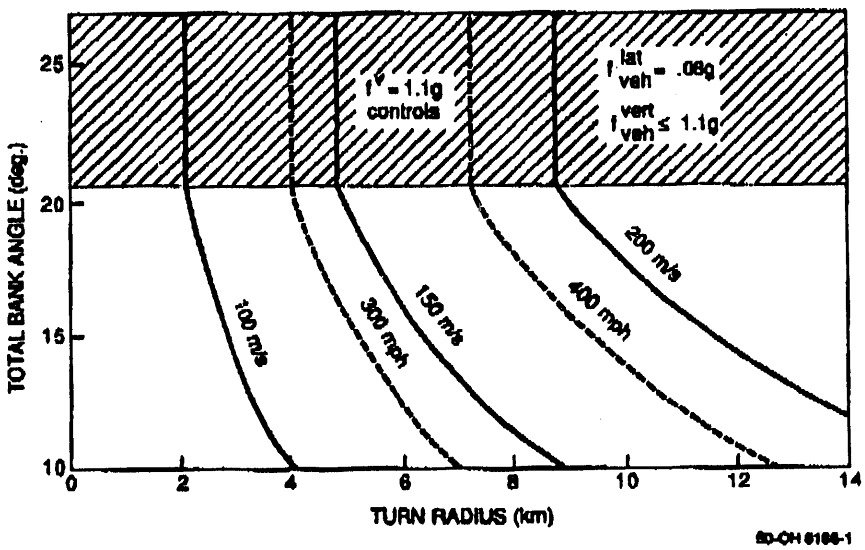



Figure 4. Example of Total Bank Angle versus Minimum Horizontal Turn Radius Relationship

# INSTITUTIONAL OBSTACLES TO THE DEVELOPMENT OF MAGLEV IN THE UNITED STATES

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## I. STATEMENT OF PROBLEM

The most imposing barriers to commercial implementation of maglev in the United States are institutional barriers -- technological challenges and requirements pale in comparison. Although further technological developments are required in each of maglev subsystems, these can be overcome with time, logic, and ingenuity. Changes in policy, regulations and congressional and parochial jurisdictional boundaries demands planned, coordinated, and sustained efforts by all interested to educate local, state and federal officials and legislators about the short and long term benefits of maglev to justify allocation of necessary funding.

## II. BACKGROUND

In 1987, Senator Daniel P. Moynihan struck out on his own with a challenge to the federal government and a vision for private industry to develop a commercial magnetically levitated system to supplement and relieve the congestion plaguing our highways and airspace. In three years, he sparked the interest of several Senators, more Representatives, and some elements of private industry. Currently, federal agencies are vying for funding and responsibility.

Senator Moynihan responded to early nonchalance and raised eyebrows of skeptics with a million dollar carrot in federal appropriations to the Army Corps of Engineers to study the feasibility of developing a commercial maglev system within the United States using American technology. Once this was accomplished, various federal agencies claimed jurisdiction and "interest" grew. Additional monies were appropriated to the Department of Transportation for establishing a cooperative Interagency Federal Maglev Initiative.

The 4-year Federal Maglev Initiative was initiated by the Federal Railroad Administration (FRA) issuing a Broad Agency Announcement for assessing current maglev technology and potential advances through limited research. Over 271 proposals were received in response to the BAA request. Contracts are currently being negotiated with those selected. The enthusiastic response helped to feed life into the maglev initiative.

In late April proposals from private industry were submitted in response to FRA's requests for proposals for a systems concept definition for a maglev design alternative to either the Japanese or German maglev designs, phase II of the initiative. A number of teams comprised of engineering firms were expected to respond, and one or more awards may be made. At the conclusion of these contracts, the Federal Interagency Maglev Coalition will decide whether additional effort and monies should be appropriated for development of U.S. maglev technology.

Maglev is competing for scarce monies with many and varied programs, including other transportation funding, technology and science funding, defense, bank bails outs, etc. all pushed by special interest industries and groups. A comprehensive implementation plan must be developed to promote maglev so it may compete equally, particularly with regard to its advantages and long term investment improved transportation, air quality, and energy conservation.

The lack of a coherent transportation policy is the primary obstacle to commercial development of maglev. The Administration continues to encourage the separate divisive structure of the transportation industries, that is reinforced by the structure of the Congressional committees and influence of interest groups. An effort must be made to establish a comprehensive policy that includes investigation of the benefits and trade-offs with competing modes of travels such as air or auto. Transportation must be viewed as a whole instead of compartments of diverse technologies and goals and funding requirements, and viewed globally to incorporate environmental and energy issues and benefits derived from comprehensive planning.

Currently air and automobile traffic accounts for more than 75 percent of our energy consumption and is the source of many air and water pollutants. To justify necessary funding for maglev or other high speed ground transportation based on electrical power, energy and environmental health issues must be addressed. The Clean Air passed last year imposes new goals for clean air in urban areas suffering from the congested conditions; this may serve as an incentive.

Efforts to promote high speed ground transportation must enlist the efforts of public, industry, and state, local and federal governments. Local and state jurisdictional boundaries must fade.

## III. RECOMMENDED RESEARCH

- Evaluate and quantify the benefits of maglev in terms of improved transportation, energy consumption, reduced costs resulting on existing modes, and environmental health.
- Evaluate the impact of "doing nothing."
- Outline a program to educate the Public and Government officials regarding the societies benefits.
- Develop a model regional development program to address and mitigate institutional barriers, including:
    - Establish regional commissions to address regional planning and development issues.

- Identify all institutional barriers such as:

  Local, State and Federal impediments to financing
  Zoning regulations
  Congressional Legislative jurisdictions
  Demographic jurisdictions.

# THRESHOLD MAGLEV RESEARCH AND DEVELOPMENT PROGRAM - A NO REGRETS APPROACH TO MAGLEV R&D

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## I. STATEMENT OF PROBLEM

High-speed transportation systems using magnetic levitation technology are likely to be implemented in the United States in the next decade. Whether this implementation will be limited to special demonstration projects or will form the foundation of a new interstate transportation network will depend directly on two things: (1) the costs and benefits of the technology and (2) on the role that the Federal Government plays in the development and/or implementation of the technology. It can be argued that even the costs and the extent to which the potential benefits of maglev technology will be realized will depend largely on the role of the Federal Government. At least three alternative paths to implementation are possible:

- An existing technology (either German or Japanese) can be implemented now or in some slightly modified version (modified by original developer).
- An existing technology can be substantially modified in a collaboration with the original developer and a U.S. group and then implemented.
- An entirely new maglev technology can be developed in the U.S. and then implemented.

The first path could lead to an operational line within 5 years. The second and third options would take about 10 years.

The role of the federal government could include activities ranging from regulation (primarily with regard to safety) to enactment of enabling legislation, to setting of national standards or to becoming a major source of R&D funding. The National Maglev Initiative (NMI) is currently conducting studies with the goal of reaching decisions late in FY92 regarding both the recommended path to be taken and the recommended role that the Federal Government should play.

There are several important benefits to initiating a Threshold Maglev R&D Program now. First, whether the Federal Government elects to fund the development of a U.S. technology or to take a less active role in an alternative approach to implementing maglev, the potential stakeholders in the public and private sectors need to be provided with a knowledge base upon which they can formulate sound decisions. The proposed Threshold Maglev R&D program provides that foundation.

Second, the 1991 NMI recommendations will probably come too late to affect the FY93 Federal Budget. Consequently, there is a high probability that a gap could be created in the maglev program in FY93. A Threshold R&D Program would provide a logical and systematic means of bridging that gap and maintaining the maglev program momentum.

Third, with the Threshold Program in place, long-lead-time activities could be initiated now that would not be permitted under the auspices of the NMI.

Finally, the Threshold Program prevents the foreclosure of alternative future options. The Federal Government could decide not to fund a major U.S. maglev development program because of short-term budget problems but then change its mind in a year or two with only a modest loss of time provided that the Threshold R&D Program remained in place.

## II. BACKGROUND

### What is the Threshold Maglev R&D Program and How is it Related to the NMI?

The NMI is directed toward reaching maglev development and implementation recommendations in FY92. Technology assessments and system concept definition studies are being funded to obtain the information needed in support of that decision-making process.

The Threshold Program on the other hand, will focus on long-term R&D and will not be limited by assumptions regarding the outcome of the NMI decision-making process. Consequently, activities can be initiated now that will not need to be completed in FY92.

The Threshold Program will parallel and be closely coordinated with the ongoing NMI. In fact, its earliest phase could be an integral part of the NMI. Its main objective will be to explore the limits of technology and extend those limits, where feasible, to obtain the most cost-effective maglev technology for the U.S. market over the next seven to ten years. The program will involve research, development, and evaluation at the pre-competitive and pre-commercial prototype stages. That is, at the stages when the information, including data and computer software, can be exchanged or transferred via public communication channels. Consequently, it will not compete with nor substitute for private sector or public/private partnership efforts to develop commercial maglev systems in the United States. It will focus on the development of innovative concepts and exploitation of advances in key technologies which when taken in combination, will provide the basis for the next generation of maglev technology regardless of the company or country that implements it in a commercial system.

### How Would the Threshold Program be Affected by the 1992 NMI Recommendations and Subsequent Congressional Actions?

The 1992 NMI decision-making process could result in a broad spectrum of possible recommendations that would presumably be followed by Congressional actions that may or may not be completely consistent with those recommendations. However, from the point of view of development of a "next-generation" maglev technology in the U.S., the extreme options are that the Federal government either will or won't fund it. These two extremes are referred to here as "go" and "no go" decisions, respectively. Of course, any position between these two extremes is possible and in any case, some Federal Agency activity (e.g., health and safety-related) will be required by Congress.

If the NMI and Congress reaches a "go" decision in FY92/93, the parallel relationship between the NMI and the Threshold Maglev R&D Program will continue uninterrupted and the technology created in the latter program will be transferred to NMI contractors in an iterative development/fabrication/test cycle having roughly a two to three-year cycle time. The objective of this iterative approach will be to develop technology in stages to yield an advanced, cost-effective commercial prototype within about ten years.

If the NMI and Congress reaches a "no go" decision in FY92/93, then the parallel relationship will cease, but the Threshold Program will continue with its research and technology development. Its products can be iteratively transferred to the private sector (either domestic or foreign) for commercialization and its knowledge base can be applied to future implementation decisions that the public/private sectors will have to make to meet future transportation demands.

## III. RECOMMENDED RESEARCH

### An Approach to Defining a Threshold R&D Program

The composition of the Threshold R&D Program will be defined by a set of governing questions decision makes must ask as they confront the problems of meeting future transportation demands in a highly constrained technical, socio-economic and political environment. A first cut at formulating the governing question follows:

1. What are the key technologies whose advancements, taken in combination, could enable a new, more cost-effective maglev technology than presently exists?

2. Are there ways to improve existing maglev technologies to enhance their cost effectiveness?

3. What the costs and benefits of existing and possible innovative maglev concepts relative to existing and possible innovative high speed rail concepts?

4. What auxiliary and system-wide considerations need to be addressed that would affect any high-speed ground transportation system that would be implemented on a national scale?

5. What will the market be for these technologies and how sensitive is that market to various technological features?

6. What are the constraints, imposed by human comfort, on system design? How well are these constraints known?

7. What are the constraints, imposed by safety considerations, on system design?

8. What are the constraints, imposed by system reliability requirements, on system design?

9. To what degree will Federal Government involvement in the R&D, commercialization, and implementation phases (1) reduce systems costs, (2) impact the rate and extent of market penetration, and (3) influence the realization of the potential benefits of the technologies?

Obviously, the Threshold Program must be fairly broad-based to be able to address such governing questions. A first cut at delineating R&D tasks for such a program is given in the accompanying table. The list includes a range of key technologies and auxiliary issues applicable to implementation/further development of the two existing foreign maglev designs and to development of a next-generation U.S. maglev design. Many topics apply to all three maglev development and/or implementation alternatives while some are applicable to non-maglev, high-speed intercity transportation systems as well.

In addition to advancing key technologies, experimental facilities in appropriate sizes must be planned, developed, and installed for the eventual testing and evaluation phases. These facilities extend from small, proof of concept experimental facilities to larger-scale facilities for evaluating intermediate and full size components, major subsystems and full-size prototype vehicles. Facilities for testing full-scale vehicles and guideways are beyond the scope of the Threshold R&D program.

Program Plan Assuming a NMI and Congressional "Go" Decision in FY92/93

The Threshold R&D program plan will be closely coordinated with NMI activities. Threshold R&D and NMI activities are shown together in the time-line chart of Figure 1. Initially, the Threshold R&D effort will focus on four areas:

1. Development and evaluation of innovative maglev concepts.

2. Taking advantage of opportunities to make advancements in key technology areas that are already being developed for other reasons (i.e., high $T_c$ superconductivity, composite materials, etc.)

3. Initiating auxiliary and system-wide considerations (e.g., biomagnetic effects)

4. Determining requirements for, and planning and preparing, small to intermediate size national test facilities.

Early results of the R&D efforts will be transferred to the NMI contractors who will incorporate them into their 1st iteration on maglev designs. Reduced-scale components and subsystems (e.g., vehicles, guideway maglev components, etc.) incorporating the state-of-the-art technologies will be fabricated by the contractors and tested using available laboratory/National testing facilities.

Threshold R&D efforts on the next iteration of key technology advancements will continue while NMI contractors focus on incorporating the fruits of the 1st iteration of key technology advancements into their designs, fabricating components and testing them. In this way, both technology development and applications to maglev vehicle and guideway designs can be conducted in parallel without delaying either activity. Several cycles of R&D, fabrication, testing and evaluation are possible. The Threshold Program transfers the technology advancements after each R&D cycle to the NMI contractors who incorporate, fabricate, test, evaluate and feedback. In practice, the technology transfer may turn out to be more of a continuous than a discrete cycle-by-cycle process. However, if feasible, a cyclic process with appropriate design "freezes" should be a more orderly way to proceed.

Program Plan Assuming a NMI and Congressional "No-Go" Decision in FY92

A "no-go" decision, as used here, means that the Federal Government will not fund a major U.S. maglev R&D effort beginning in FY94. It may turn out that Congress elects to postpone such an effort or give it up altogether. Given the latter choice, the government may choose further to play a completely passive role, allowing the market place forces to decide on future maglev implementation/development options. On the other hand, Congress may elect to mandate Federal Agencies to play any of several possible active roles in helping to select the best technology, develop national standards, define enabling legislation, etc. However, regardless of the Federal government roles, the Threshold Program will cease to have NMI-funded contractors as commercialization partners. In their place, the private sector, perhaps in cooperation with local stake-holder groups, will likely become commercialization partners and the technology advancements, knowledge base and technical expertise will be transferred to them as needed. In addition, the Federal Agencies and other public entities will receive technical information as needed to help them fulfill their respective roles.

The Threshold Program will still focus on R&D activities at the pre-commercial and pre-competitive levels and on the auxiliary and systems-wide considerations listed in the table. The cyclic process of R&D, incorporation into maglev-related components, testing and evaluation would be carried on under the auspices of the Threshold Program rather than at the NMI Program. Hence, many of the same topics listed in the table would be addressed and the time lines would remain essentially the same as in Fig. 1, except, or course, that the NMI-related tasks would be eliminated or possibly replaced with non-Federal government-supported efforts of public/private entities.

Funding - How Should it be Funded?

The Threshold R&D Program could be funded as a separate program or as an inseparable part of the NIM.

There are, basically, three arguments against making the Threshold R&D Program an inseparable part of the NMI. First, the longevity of the NMI is quite uncertain beyond FY92. There is no Congressional mandate at present, to continue the program beyond that date. Second, the focus of the present phase of the NMI is on the preparation of recommendations to Congress and the Administration in FY92, whereas that of the Threshold R&D Program is on long-term R&D. Third, the nature of the two programs is different. Whereas the Threshold program is directed toward technology development, the NMI long-term goal is to develop and implement a maglev transportation system that presumably incorporates advanced technology. That is, the Threshold Program develops technology, and the NMI uses it. If the programs are inseparable, there is likely to be a tendency of the users to try to restrict the scope of the developers too much.

There are also several arguments in favor of either making the Threshold R&D Program an inseparable part of the NMI, or at least closely linking their funding. First, in FY92 and 93, with proper structuring, both programs could share many tasks in common. The initial information obtained from long-term R&D efforts could serve the needs of the NMI FY92 decision-making process. Subsequently, the timely transfer of technology from the technology developers to the users may be expedited. Second, it may be easier to insure that the R&D efforts are more focused on the needs of the technology users (i.e., the maglev system designers). Third, initial funding is already available for FY91 and is in the President's Budget Request for FY92 for the NMI. A portion of that funding could be allocated to the Threshold R&D Program.

Regardless of which method of funding is adopted, three considerations must be properly accounted for: program longevity, coordination of development efforts with technology user needs, and the need to begin certain long-lead time tasks as soon as possible.

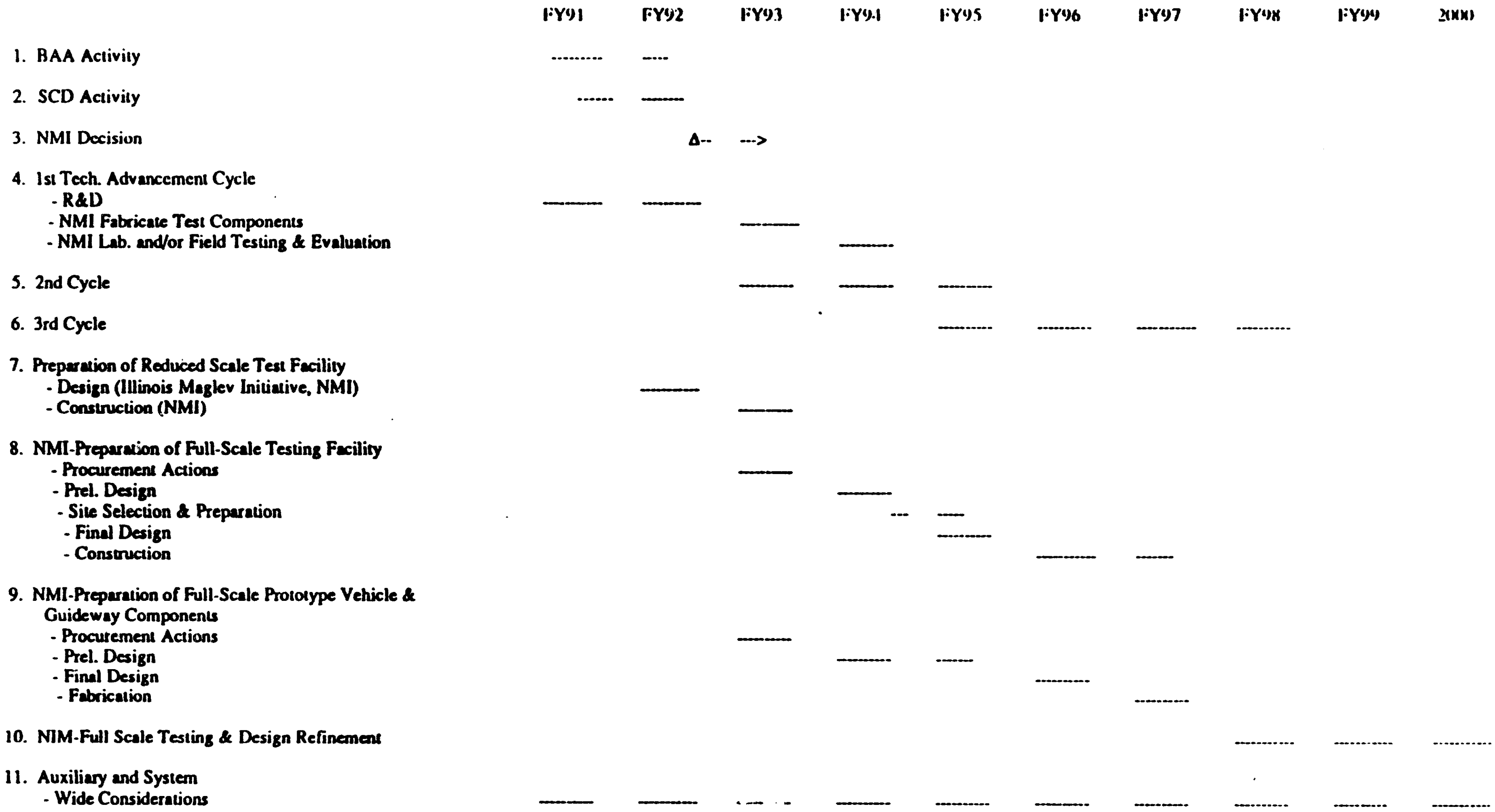


**Fig. 1 Combined NMI and Threshold Maglev R&D Program**

# END

# DATE FILMED

12/3/91