MAGNETIC LEVITATION SYSTEMS FOR FUTURE AERONAUTICS AND SPACE RESEARCH AND MISSIONS

Presentation at Workshop

TRANSPORTATION BEYOND 2000:
TECHNOLOGIES NEEDED FOR ENGINEERING DESIGN

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ABSTRACT

The objectives, advantages, and research needs for several applications of superconducting magnetic levitation to aerodynamics research, testing, and space-launch are discussed. Applications include very large-scale magnetic balance and suspension systems for high alpha testing, support interference-free testing of slender hypersonic propulsion/airframe integrated vehicles, and hypersonic maglev. Current practice and concepts are outlined as part of a unified effort in high magnetic fields R&D within NASA. Recent advances in the design and construction of the proposed ground-based Holloman test track (rocket sled) that uses magnetic levitation are presented. It is projected that ground speeds of up to Mach 8 to 11 at sea-level are possible with such a system. This capability may enable supersonic combustor tests as well as ramjet-to-scramjet transition simulation to be performed in clean air. Finally a novel space launch concept (Maglifter) which uses magnetic levitation and propulsion for a re-usable "first stage" and rocket or air-breathing combined -cycle propulsion for its second stage is discussed in detail. Performance of this concept is compared with conventional advanced launch systems and a preliminary concept for a subscale system demonstration is presented.
OUTLINE OF PRESENTATION

- MAGNETIC LEVITATION R & D AT NASA
  - Rationale for infrastructure building

- APPLICATIONS OF MAGNETIC LEVITATION
  - MSBS
  - HOLLOMAN AFB TEST TRACK UPGRADE
  - MAGLIFTER / LUNATRON

- MASS TRANSPORTATION -- "MAGLEV"
  (airplanes flying in extreme ground effect)
    - TECHNOLOGY NEEDS
    - RECENT DEVELOPMENTS IN JAPAN
Principles of superconducting linear motor car MAGLEV

### Principle of propulsion

Magnetic levitation and repulsive force are utilized. The propulsion coils, installed on the side walls of the guideway, are energized by three-phase alternating current from a substation, creating a shifting magnetic field. The on-board superconducting magnets are attracted and pushed by the shifting field, propelling the Maglev vehicle.

### Principle of magnetic levitation

- **Vertical suspension**
  - The "S"-shaped levitation coils are installed on the side walls of the guideway. When the on-board superconducting magnets pass at high speed several centimeters below the axes of these coils, an electric current is induced, making them act as electromagnets temporarily. As a result, the forces which push the superconducting magnet upwards and ones which pull it upwards act simultaneously, thereby levitating the Maglev vehicle.

- **Lateral guidance**
  - The levitation coils facing each other are connected under the guideway, constituting a loop. When a running Maglev vehicle, that is, a superconducting magnet, displaces laterally, an electric current is induced in the loop, resulting in a repulsive force acting on a levitation coil near the car and an attractive force acting on another levitation coil farther apart from the car. Thus, a running car is always located at the center of the guideway.
MAGNETIC LEVITATION  R&D at NASA

- In recent years, NASA and VPI (Virginia Polytechnic Institute) have provided support to the National Maglev Initiative (NMI) in the Department of Transportation’s Federal Railroad Administration (FRA)
  - Support has been limited in scope, focusing on aerodynamics analyses of alternate maglev vehicle configurations
  - Other aeronautical technologies (structures, stability and control, noise, etc) are applicable

- Independently, NASA personnel have also examined various concepts and applications of magnetic levitation and related technologies for Agency purposes
  - Wind tunnel model magnetic suspension and balance systems (MSBS) applications
  - Magnetic bearings (superconducting and rare earth magnet) applications
  - High temperature superconductor materials and manufacturing (e.g., wire)

- Building on past studies, during the past 1.5 years, an intensive ad hoc examination has been conducted of the possibilities for application of maglev for space launch (i.e., the 'MagLifter' concept)
  - The "MagLifter" concept: Studies have focused on rocket-propelled vehicles
  - Potential applications include launch of small, medium and large Earth to Orbit (ETO) vehicles (Rocket, Airbreathing and Hybrid) as well as launch of hypersonics research X-vehicles
  - Coordination with USAF on the planned maglev upgrade of the high speed rocket-sled test track at Holloman AFB (a potential capability Mach 11+ using Maglev)
**Rationale for Maglev at NASA**

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**NASA Systems-Level Space Opportunities**
- Small Earth-to-Orbit Transportation ("Mark II" Catapults)
- Large Earth-to-Orbit Transportation ("Mark III" Catapults)
- Others

**NASA Systems-Level Aeronautics Opportunities**
- Hypersonics Research X-Vehicle Launcher ("Mark II" Catapult)
- Magnetic Suspension & Balance
- Hypersonic Test Track Research
- Others

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**Dual-Use Technology Commercialization Systems-Level Opportunities — Aero/Space**
- Maglev Ground Transportation
  - Others

**Dual-Use / NASA Secondary Applications**
- Magnetic Bearings (e.g., pumps, CMGs)
- Superconducting Materials Components (e.g., wire)
- Power Systems (distribution, storage, etc.)
- Potential Other Government Applications
  - Others
Potential Impact of the Introduction of High-Temperature Superconductors

- High-Temperature (high 'Tc') superconductors could have major impacts in the areas of:
  - Cryogenics
  - Thermal stability of superconductor systems
  - Wire manufacturing and design
  - Vehicle magnetic shielding
  - System service and maintenance

- High Tc superconductors may also have moderate impacts in the areas of:
  - Levitation and guidance systems
  - System stress and fatigue effects
  - Vehicle structure and suspension
  - Guideway system design trades/choices (e.g., power; curves; track type)
  - Design-Level issues (capital costs, operating costs, human factors)
Maglev-MagLifter R&D Program Concept
Mapping Strategic Goals into Technology Objectives

<table>
<thead>
<tr>
<th>High-Leverage R&amp;D Opportunities</th>
<th>MagLifter (Space Launch)</th>
<th>Aeronautics (R&amp;D Applications)</th>
<th>Maglev (Ground Transport)</th>
<th>Secondary Opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory-Level Proof-of-Concept</td>
<td>Low Mass Superconductors High Tc Superconductors High-Efficiency EM Propulsion</td>
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<tr>
<td><strong>Core Technologies and Capabilities</strong></td>
<td><strong>Testbed Demonstrations</strong></td>
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<tr>
<td>Very High-Acceleration EM Propulsion Low-Cost Guideway Light-Weight Vehicles</td>
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<td>Magnetic Bearings SMES Precision Tunnel Systems CMGs</td>
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<tr>
<td><strong>Technology and Systems Validation</strong></td>
<td><strong>System-Level Demonstration</strong></td>
<td><strong>System-Level Demonstration</strong></td>
<td><strong>System-Level Demonstration</strong></td>
<td>n/a</td>
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<tr>
<td>Mark I Demo Mark II Demo (R&amp;D for Mark III development)</td>
<td>Hypersonic Test Track Experiments Sub-Scale Launch Demo (Mark II scale)</td>
<td>Relevant System-Level Demos (Mark I, Mark II)</td>
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MSBS Applications

Support Interference-Free Aerodynamic Testing
- Transport cruise drag
- High angle-of-attack aerodynamics
- Generic interference evaluation
- Dynamic stability

Dynamic Stability Testing
- Forced oscillation - unlimited trajectory opportunities
- "Modal" oscillations
- Random excitation - system identification

Unsteady Aerodynamics
- Vortex flows / vortex breakdown
- Unsteady separation and wakes
- Dynamic stall

Unconventional Testing
- Store separation.
- Multi-body separation
EXAMPLES OF SOME MODEL SUPPORT PROBLEMS

- Afterbody drag
- Trim & tail loads
- Yaw damping
## Future Applications

### Program Focus

<table>
<thead>
<tr>
<th>Area</th>
<th>Description</th>
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<tbody>
<tr>
<td>Aerodynamics</td>
<td>Unsteady aerodynamics, dynamic stability, support interference elimination, unconventional testing</td>
</tr>
<tr>
<td>Technology development</td>
<td>MSBS is a powerful technology driver</td>
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<tr>
<td>Specific Technologies</td>
<td>Position and attitude sensors; control systems and algorithms; magnetic configurations; electromagnet design and analysis; superconductivity</td>
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<tr>
<td>Key Spin-Off Technology</td>
<td>Powerful, AC-capable, high temperature superconducting electromagnets</td>
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TRACK MISSION

- SIMULATES BY MEANS OF ROCKET SLEDS
  - Critical portions of flight trajectories
  - Dynamic events
  - Special environmental conditions
- BRIDGES THE GAP BETWEEN LABORATORY AND FLIGHT
- SHIFT RISK OF FAILURE FROM FLIGHT TO GROUND TESTING

TRACK CHARACTERISTICS

- Length: almost 10 miles
  Sled velocities at 10,000 ft per sec
- Two rails: 50,788 feet
- Narrow gage rail: 15,200 feet
- Gages: 7 feet and 26.31 inches
- Alignment: within 0.005 inch
- Continuously welded

PROVEN TEST CAPABILITY

<table>
<thead>
<tr>
<th>AIRCRAFT</th>
<th>ENVIRONMENT</th>
<th>OTHER</th>
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<tbody>
<tr>
<td>- Crew Escape</td>
<td>- Rain / Ice</td>
<td>- Warhead / Fuse</td>
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<tr>
<td>- Airblast</td>
<td>- Aerothermal</td>
<td>- Impact</td>
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<tr>
<td>- Birdstrike</td>
<td>- Dust</td>
<td>- Decelerators</td>
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<tr>
<td>- Aeropropulsion</td>
<td>+ High G</td>
<td>- Survivability</td>
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<tr>
<td>- Munitions Launch</td>
<td>- Hypersonic</td>
<td>- Vulnerability</td>
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<tr>
<td>- IRCM</td>
<td></td>
<td>- Lethality</td>
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<th>MISSILES</th>
<th>OTHER</th>
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</thead>
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<tr>
<td>- Guidance</td>
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<tr>
<td>- Aerodynamics</td>
<td>- Impact</td>
</tr>
<tr>
<td>- Aeroelastics</td>
<td>- Decelerators</td>
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<tr>
<td>- Dispenser</td>
<td>- Survivability</td>
</tr>
<tr>
<td>- Seekers</td>
<td>- Vulnerability</td>
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<tr>
<td>- Components</td>
<td>- Lethality</td>
</tr>
<tr>
<td></td>
<td>- Live Fire</td>
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</table>
HOLLOMAN
HIGH SPEED TEST TRACK

"ON TRACK FOR TOMORROW"

TRACK MISSION

- Simulates by means of rocket sleds
  - Critical portions of flight trajectories
  - Dynamic events
  - Special environmental conditions

- Bridges the gap between laboratory and flight

- Shift risk of failure from flight to ground testing

TRACK CHARACTERISTICS

- Length: almost 10 miles
- Two rails: 50,788 feet
- Narrow gage rail: 15,200 feet
- Gages: 7 feet and 26.31 inches
- Alignment: within 0.005 inch
- Continuously welded

TEST VELOCITIES: Sled velocities approaching 10,000 feet per second

ADVANTAGES OF TRACK TESTING

- Full-scale testing
- Realistic simulations
- Accurate timely results
- Cost-effective approach
- Flight-test environment
- Test item recovery
- Testing of prototypes
- Early development risk reduction
HOLLOMAN TEST TRACK - WHY MAGLEV?

- CURRENT CAPABILITY:
  - 1.5 - 2.4 KM/SEC
  - VIBRATIONS MAY EXCEED FLIGHT ENVIRONMENT

- LIMITATIONS
  - RAIL INDUCED LOADS/IMPACTS
  - PROPULSION
  - SLIPPERS
  - "and with MAGLEV capability"

- ELIMINATES RAIL IMPACT INDUCED LOADS/VIBRATION
  - PAYLOADS CAN BE MORE REALISTIC
  - REDUCED SLED STRUCTURE
  - HIGHER VELOCITIES: 3.5 KM/SEC +

- ELIMINATES SLIPPER WEAR
HOLLOMAN AFB MAGLEV TRACK UPGRADES

Option 1: Extend existing track 7 km
speed capability 2.5 km/sec → 2.7 km/sec
Vibration Levels Unchanged

Option 2: Extend existing track 7 km
use MAGLEV on extension
speed 2.5 km/sec → 3.5 km/sec
Much Reduced Vibration

Option 3: Extend existing track 9 km
use MAGLEV on extension
speed 2.5 km/sec → 3.7 km/sec
Much Reduced Vibration
POTENTIAL HYPERVELOCITY MAGLEV APPLICATIONS

- HYPERVELOCITY IMPACT STUDIES (3 - 4 KM/SEC
  - Lethality Tests
- FIRST-STAGE BOOST OF ORBITAL AND SUB-ORBITAL PAYLOADS
  - Environmentally compatible launch systems
- FLIGHT TESTS/WIND TUNNEL TESTS AT HYPERVELOCITY
  - Piggy-back experiments (free-flight cone-cylinders)
  - Tests of models at full-scale
  - Boundary Layer Transition (no tunnel noise, M8)
  - Materials/Actively Cooled structures
- HIGH AERODYNAMIC EFFICIENCY PROJECTILES USING AIR-BREATHING ENGINES - storable hydrocarbon fuel scramjet testing to Mach 11 + in non-vitiated air and q > 10,000 (T/W = 100/200)
LEVITATED TEST SLED ASSEMBLY

- Structural Hoops
- Test Vehicle
- Coil Support Structure
- Wing Modules
- Superconducting Coil Modules
- Leading Edges
MAGLEV HIGH-SPEED ROCKET SLED DESIGN ISSUES

Aerodynamics
- Drag reduction
- Controllability
- Viscous effects
- Channel flow

Stability & Control
- Flexibility
- Time dependent vehicle characteristics
- Time dependent environment

Guideway Integration
- Systems approach
- Wings

Aeroheating
- Shock impingement
- High gradients
- Protuberances

Structural Design & Analysis
- Sled
- Wing/s
- Light weight
- High strength
- High temperatures

Thermal Management
- Active/passive systems
- Reusable/refurbishment
- Heat leaks
- Thermal protection
PICTURE of MAGLIFTER CONCEPT
MagLifter — non-Aerodynamic HRV
Configuration A "Mark III" Full-Scale System

Other Facilities
Not Shown
(e.g., Control
Center,
Landing Area,
Storage, etc.)

Primary Power
System
(e.g., SMES
Option)

Staging Facility

Vehicle
Fueling and
Final
Check-Out

Gas
Membrane
(Design
Option)

HRV
Release
Point

LAUNCH

Engine Start for Pre-
Release Check-Out
(Design Option)

45 deg.
(55 deg. Design Option)

Decelerator
Guideway

Total Ascent:
Approximately
6500 feet

10,000 ft
(approx.)

3,500 ft
(approx.)

0.5-1.0 mile

2.5 mile

Peripheral
Power
Storage
Units

Tunnel
(Design
Option)

Accelerator
Guideway

Power Storage
Sub-Stations

Ref. Vehicles:
Rocket ≤ 2.0 Mlbs
@ 600 mph
A/B-R ≤ 0.5 Mlbs
@ 1200 mph

Highly Reusable Vehicle
(HRV)

MagLev Accelerator-
Carrier Vehicle

Structural Supports
(Distribution of Loads on Payload
Vehicle)

SYSTEM
CROSS-SECTION
MagLifter — Aerodynamic HRV
Configuration B "Mark III" Full-Scale System

Ref. Vehicles:
Rocket ≤ 2.4 Mlbs
@ 600 mph
A/B-R ≤ 0.6 Mlbs
@ 1200 mph

Aerodynamic-Highly Reusable Vehicle (A-HRV)

System Cross-Section

MagLev Accelerator-Carrier Vehicle

Structural Supports (Distribution of Loads on Payload Vehicle)
MagLifter – Payload Sensitivity Analysis
(Sensitivity to Altitude and Velocity)

**Analysis Reference Case:**
39,000 LBS TO LEO (APPROX.)

**Case 2**
600 MPH; 45 DEG.

**Case 1**
300 MPH; 45 LEG.

**Benchmark:** SSTO (R)
1.2 MILLION LBS GLOW,
16,000 LBS TO LEO (APPROX.)
0 MPH, 90 DEG. ATTITUDE, SEA LEVEL

**Altitude**
(Feet above Sea Level)
MagLifter: Payload Sensitivity Analysis
(Sensitivity to Attitude and Velocity)

**Analysis Reference Case:**
- 39,000 Lbs to LEO (Approx.)

**Case 2**
- 600 MPH, 10,000 FT

**Case 1**
- 300 MPH, 10,000 FT

**Benchmark:**
- SSTO (R)
- 1.2 Million Lbs GLOW,
- 16,000 Lbs to LEO (Approx.)
- 0 MPH, 90 Deg. Attitude, Sea Level

**Injected Mass**
(Klbs, to 28.5 deg. @ 120 nm)

**Payload**
(Klbs, to 28.5 deg. @ 120 nm)

**Attitude**
(Degrees from horizontal; launch from 10,000 ft)
MASS
TRANSPORTATION
MAGLEV

RECENT DEVELOPMENTS IN
JAPAN
Selected Maglev Technology Issues

- The following are some of the key technology-related issues facing maglev applications for ground transportation
  - Aerodynamics (i.e., reducing drag at high speeds; entering/exiting tunnels)
  - Communications with the vehicle; control of the vehicle
  - Magnet design, cryogenics, helium management
  - High speed switching; speed, acceleration and braking
  - Primary and secondary suspension
  - On-board power; system power supply (interface with utility, substations)

- Other key design and development issues include:
  - System development and implementation cost (guideway, vehicles)
  - Magnetic field levels in the vehicle (passenger safety)
  - Passenger ride quality (transient g-forces inside the vehicle)
  - Route selection and system operations
  - 'Operations and maintenance' of the system (logistics, cost, emergencies)
  - Noise (inside the vehicle, outside the vehicle)

Major R&D task: make construction costs competitive with that of the conventional wheel - rail system.