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The MagLifter: An Advanced Concept Using Electromagnetic Propulsion in Reducing the Cost of Space Launch

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ABSTRACT

Achieving an affordable and reliable launch infrastructure is one of the enduring challenges of the space age. In a marketplace dominated by expendable launch vehicles (ELVs) grounded in the technology base of the 1950s and 1960s, diverse innovative approaches have been conceived since 1970 for reducing the cost per pound for transport to low Earth orbit LEO. For example, the Space Shuttle – a largely reusable vehicle – was developed in the 1970s with th goal of revolutionizing Earth-to-orbit (ETO) transportation. Although the Shuttle provide many important new capabilities, it did not significantly lower space launch costs. During the same period, a variety of other launch requirements (e.g., for vehicle research and development (R&D) and microgravity experiments) have been met by relatively expensive, typically rocket-based solutions (e.g., rocket sleds and sounding rockets).

There are several basic strategies for cost reduction, including: (1) reducing the cost of hardware expended in launcher systems per pound of payload, (2) increasing the reusability per flight of highly reusable vehicles (HRVs), and (3) for both of these, reducing the cost of launch operations. A variety of space launch concepts are still under study in this context, ranging from single-stage-to-orbit (SSTO) vehicles to 'big-dumb-boosters', from air-breathing hypersonic ETO vehicles like the National Aerospace Plane (NASP) to advanced rocket concepts such as space nuclear thermal propulsion (SNTP). Some exotic concepts involving 'gun-type' systems have also been studied.

However, past analyses of launch systems involving electric propulsion have been largely limited to electromagnetic (EM) versions of 'cannons' such as rail guns and coil guns. Despite significant theoretical advantages, these EM systems have had both technical and programmatic difficulties in maturing beyond R&D and prototype-level demonstrations.

A new approach, involving the use of superconducting magnetically-levitated ("maglev") vehicles has been developed. This ETO concept, the "*MagLifter*", combines the technology base of maglev systems proposed for terrestrial applications with the best planned improvements in ELV and reusable vehicle systems. Together, the result suggests dramatic improvements in ETO costs may be possible. The *MagLifter* draws on a heritage of EM launch concepts in fiction (many) and the technical literature (few), but embodies several new technical characteristics which have not been thoroughly considered to date.

The *MagLifter* concept is summarized in the context of a brief review of EM launch approaches and maglev R&D efforts. The results of preliminary analyses are then presented. In addition, the potential benefits of the concept, including strong dual-use technology R&D content are sketched. Finally, some projections concerning potential directions for future study and development of the concept are discussed.

INTRODUCTION

Achieving an affordable and reliable launch infrastructure is one of the enduring challenges of the space age. In a marketplace dominated by expendable launch vehicles (ELVs) grounded in the technology base of the 1950s and 1960s, diverse innovative approaches have been conceived since 1970 for reducing the cost per pound for transport to low Earth orbit LEO. For example, the Space Shuttle – a largely reusable vehicle – was developed in the 1970s to revolutionize Earth-to-orbit (ETO) transportation. During the same period, a variety of other launch requirements (e.g., for vehicle research and development (R&D) and microgravity experiments) have been met by relatively expensive, typically rocket-based solutions (such as rocket sleds and sounding rockets).

There are at least basic strategies for cost reduction: (1) reducing the cost of hardware expended in launchers per pound of payload, (2) increasing the reusability per flight of highly reusable vehicles (HRVs), and (3) for both of these, reducing the cost of launch operations. A variety of space launch concepts are still under study in this context, ranging from single-stage-to-orbit (SSTO) vehicles to 'big-dumb-boosters', from air-breathing hypersonic ETO vehicles (like the National Aerospace Plane, NASP) to advanced rocket concepts (such as space nuclear thermal propulsion (SNTP). Some exotic concepts involving 'gun-type' systems have also been studied.

However, past analyses of ETO systems involving electromagnetic (EM) propulsion have been largely limited to EM versions of 'cannons'; e.g., coil guns. Despite significant theoretical advantages, however, these EM systems have had technical and programmatic trouble in maturing beyond the R&D and prototype-level.

A new approach, involving the use of superconducting magnetic-levitation ("maglev") has been developed. This concept, called "MagLifter", is a catapult that uses maglev to achieve dramatically augmented payload capacity in ETO transportation systems, while reducing mission costs. Figure 1 provides a conceptual diagram of the MagLifter system.

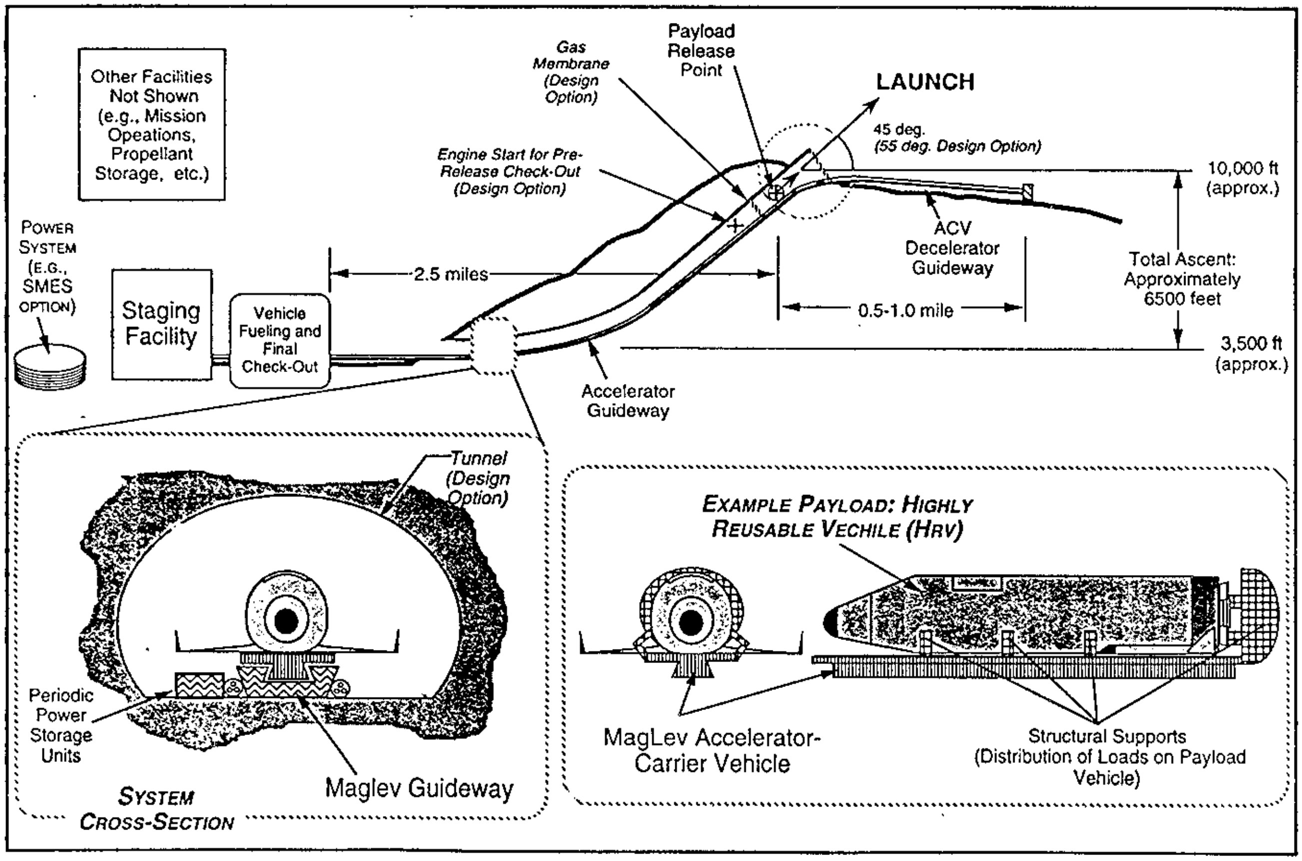

Figure 1 Top-Level Diagram of a MagLifter system (large-scale reference version)

Unlike other "gun" concepts, MagLifter does not require extremely high accelerations, does not involve radical changes in payload (i.e., spacecraft) design or components, and does not require very high launch rates to achieve economical operations. Instead, MagLifter marries the promise of low-cost EM launch — popularized in fiction — with current engineering ideas for improvements in systems and operations for space launch (e.g., ETO). The potential appears to exist for a significant reduction in the cost (per pound of payload) to LEO for a wide range of payload sizes and launch vehicle concepts.

MagLifter involves the application of superconductive magnetic levitation (maglev) technology – developed for ground transport – to the challenge of reducing the cost of space launch.

This is a summary paper describing the MagLifter concept and, hopefully, providing a point of departure for additional studies of the diverse array of issues and topics – ranging from technology development challenges to alternate system applications – that need further study.

BACKGROUND

Gun Launch Concepts

Various gun-based approaches to ETO transportation – with varying degrees of feasibility – have been invented, beginning in the last century with the fictional cannon used by Jules Verne in his novel concerning the first lunar flight. The essence of these concepts is to use a single, massive impulse (provided by the gun) to directly (or very nearly directly) propel a payload into space. Some of the most famous of these have involved very large, black powder cannons. However, in reality such guns have limited muzzle velocities and lack the potential for direct shots to LEO. Recent developments – driven by Strategic Defense Initiative Office (SDIO) – have involved other 'explosive' concepts such as 'light gas guns' (which use a gas such as Helium as a working fluid) and EM gun concepts, (such as coil guns and rail guns) which expel a projectile at much higher speeds. Some of these concepts have been demonstrated at an R&D level with sufficient fidelity to suggest that – given time and money – they could be brought into operational use. However, all of them have several severe constraints that limit their potential utility.

In addition, all gun concepts are limited in the low-end cost performance that can be achieved in operations because so much of the hardware – except for the gun itself – is expended with each launch, including the sabot, the projectile's heat shield, and the orbit insertion propulsion module. Only for very aggressive traffic models (i.e., high numbers of launches per year) do the economies of scale drive the cost per pound (to LEO) into competitive ranges. (For example, as many as 4 launches per day may be needed to achieve cost goals for some gun concepts.)

Catapults in Space Launch.

There have been a number of papers published and concepts developed for the use of EM (and rocket-powered) catapults in space launch systems. For example, in the early 1960s, a study was conducted at Holloman AFB on the effects of changing initial state vectors on launch to orbit performance.[1] Other concepts were also put forward during that same decade. In the mid-1960s, the "Hyperion" concept was developed, in which an Apollo-derived, large scale SSTO vehicle was to be launched from a rocket-powered sled and track running up the side of a mountain.

Electromagnetic launchers were considered extensively in the 1970s for applications on the lunar surface. These scenarios typically involved the launch of extremely large amounts of Lunar materials for use in the construction of Solar Power Satellites (SPS) in high or geostationary Earth orbit. Concepts included 'rail guns' and co-axial concepts such as 'coil guns'. However, preliminary R&D and studies did not result in a major programmatic thrust in this area.

In the 1980s, consideration of a number of EM catapult/gun concepts continued. Most of these involved achieving very high velocities at the release of the vehicle (or payload) being launched, with the release being made at an angle at or near 90 degrees from the horizontal. In some cases the length of the catapult was driven to absurd extremes in the attempt to reduce otherwise very high acceleration loads

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[1] This study from 1964 did not address the question of how the initial state vector was created – i.e., what type of catapult might be used. Nevertheless, this study obtained very promising and early analytic results in support of low speed catapult launch (at angles up to 40 degrees from the horizontal).

during the launch. An exception to this rule was the class of concepts considered for launching largely aerodynamic and potentially air breathing ETO vehicles such as the NASP. In a concept of this type, a horizontal track and carrier vehicle are used to accelerate a NASP-like vehicle to sub-sonic take-off speeds on a horizontal runway. Such a system – which could be electromagnetic (e.g., LMATO, the Linear-Motor-Assisted Take-Off system) – replaced the need for a massive landing gear system as well as providing initial velocity.[2] However, neither high-speed / high-angle, nor low-speed /horizontal EM guns or catapults were given serious consideration for use in developing space launch .

During the three decades of the 1960s, '70s, and '80s, however, there were other developments being made in the application of EM systems to ground transportation that may allow a transformation in how EM-assist is appraised for space launch applications.

Maglev for Ground Transportation

The concept of using magnetic forces for ground transportation has existed since the 19th century. For example, before 1910 Robert Goddard made a proposal for a tunnel-based EM train system for high-speed transport in New England. In 1966, such ideas became feasible when two U.S. researchers, James Powell and Gordon Danby, invented the concept of applying superconducting magnetic systems (SMS) for magnetic levitation (maglev) transportation systems.

During the last 30 years, diverse maglev R&D programs have been implemented. Two principal approaches have been developed for levitation: attractive, Electromagnetic Suspension (EMS) and repulsive, Electrodynamic Suspension (EDS).[3] For both levitation systems, a linear synchronous motor (LSM), or derivative, would probably be used for propulsion.

Baseline technologies for superconducting and non-superconducting maglev are quite mature. Various concepts were pursued in the U.S. in the late 1960s and the early 1970s, including some sub-scale demonstrations. However, U.S. funding has been intermittent and most U.S. programs were canceled in the 1970s. Conversely, Japan has been steadily developing EDS maglev for 20 years. In fact, 10 years ago, the Japanese National Railway demonstrated an unmanned vehicle at more than 300 mph on an open-air, 4-mile track. Current Japanese plans call for an EDS system to be constructed between Tokyo and Osaka in the post-2001 timeframe. Similar maglev developments in Germany have focused on the EMS levitation approach. The German TR-07 system has been operated by Transrapid International, Inc., at speeds near 300 mph.

At present, U.S. interest in maglev remains strong, albeit frustrated. The focus of this interest has been the Department of Transportation (DOT) Federal Railroad Administration (FRA), which managed the National Maglev Initiative (NMI). Suspended due to budget pressures in Winter 1994, the NMI funded several studies and R&D efforts that were targeted toward a demonstration maglev system in a high-density urban corridor (such as the Northeast). This demonstration would have been in the 300 mph-class, using superconducting magnetic systems (SMS) for both levitation and propulsion. At present, the FRA is continuing its studies to determine the economic viability of introducing maglev into the U.S. transportation infrastructure.

In addition, the Department of Defense (DOD), U.S. Air Force (USAF) at Holloman AFB in Southern New Mexico has initiated a program to use SMS for levitation in an upgrade of the Base's track for the very-high-speed rock-propelled sled runs. The target in this development is speeds in the range of 7-10 times the speed of sound on an open-air operational track.

On the basis of diverse studies and development projects, estimates of costs for maglev systems have been developed by various organizations. For a guideway in the 300+ mph class, cost estimates range from $ 10 to 20 million per mile. For this guideway, estimated costs for maglev vehicles are on the order of $ 3 to 5 million per vehicle (for a payload of approximately 50,000 lbs.). In addition, annual operations and maintenance (O&M) costs for these systems are projected to be quite modest (e.g., annual maglev O&M has been estimated to be on the order of 1% of capital costs).

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[2] There have also been a number of developments in the use of EM systems to replace traditional steam-drive catapults used on aircraft carriers; these are, however, not the subject of this paper.

[3] Either of these may be suitable for MagLifter.

Development of a New Concept

Past space launch studies make it clear that new systems and new concepts will be needed to truly reduce space launch costs. However, using current and near-term traditional technologies, the 'margin' for achieving engineering goals in new systems may be very close. R&D in maglev for ground transportation applications and a reexamination of existing gun and EM launch concepts suggest that a hybrid approach – such as MagLifter – may be a partial answer to the space launch cost challenge.

DESCRIPTION OF THE MAGLIFTER CONCEPT

The overall architecture of the MagLifter system consists of the following major elements: the catapult, structural support systems, power systems, and supporting systems. Figure 2 provides a top-level illustration of this system architecture. The description which follows of each of these elements corresponds to a large scale version of the MagLifter.

The Catapult. The MagLifter catapult includes three major component systems:

- **The Maglev Guideway** – The maglev guideway is the second half of the major system element of a maglev-based catapult launch system. Central questions associated with the guideway include the means and cost of construction of the system, tolerances and control, and the structure and structural dynamics (see the paragraph that follows). For a full-size system, the guideway would be approximately 3-4 miles in length, including a 2.5 mile accelerator system and a 0.5-1.0 mile ACV decelerator. In the reference concept, the accelerator system will be enclosed in a tunnel (or pressurized tube). This tunnel system may (if required for a particular launch) be filled entirely or partially with Helium gas – with a low density and low drag forces, and a high speed of sound.[4]
- **Accelerator-Carrier Vehicles (ACVs)** – The fully-reusable accelerator-carrier vehicles (ACVs) are the first half of the major element of a maglev-based catapult launch system. The ACVs provide the initial acceleration for the vehicles to be launched. These carriers, which may need to be 'ganged' for launching larger vehicles, would accommodate 'cradles' capable of structural support to vehicles during acceleration as well as rapid, controlled release at the appropriate point in the catapult launch sequence. They would also provide any needed support for vehicles during the launch sequence (approximately 1 minute in duration).[5]
- **Accelerator-Carrier Staging Facility** – a carrier servicing and staging facility will be needed for maglev carrier staging, vehicle-carrier integration, launch vehicle staging (specific to vehicles and payloads), servicing and maintenance facilities, and an operations control.[6]

Structural Support System. A large maglev catapult would require substantial structural support for effective operations. A central design trade (cited below under issues for further study) involves the question of whether or not to place the guideway: (a) on a 'trestle" on the exterior of a mountain, (b) inside a 'cut' made into the side of a mountain, or (c) inside a tunnel' inside the mountain.

Implicit in the trade just cited, of course, is the assumption that the system must use a natural feature – i.e., a mountain – as the foundation for the structural support system. This assumption might be premature. For example, a Japanese concept recently presented (see the bibliography) suggests that an extremely large, engineered structure might be used in lieu of a natural structure, such as mountain as the basis for mechanical support for an electromagnetic

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[4] Interestingly, for other reasons, Helium is also used in light gas gun concepts. For MagLifter, consideration may also be made of operation in a very low pressure air environment (near vacuum) for comparison.

[5] Since the total elapsed time from Staging Facility to exit / launch is approximately 1 minute, it is assumed that no elaborate on-board vehicle support systems (e.g., for maintaining cryogenic fluids in vehicle tanks) will be needed.

[6] By the nature of the concept, MagLifter operations will depend upon rapid turn-around, low-cost (submarine-style) launch operations, including servicing and maintenance of the carriers.

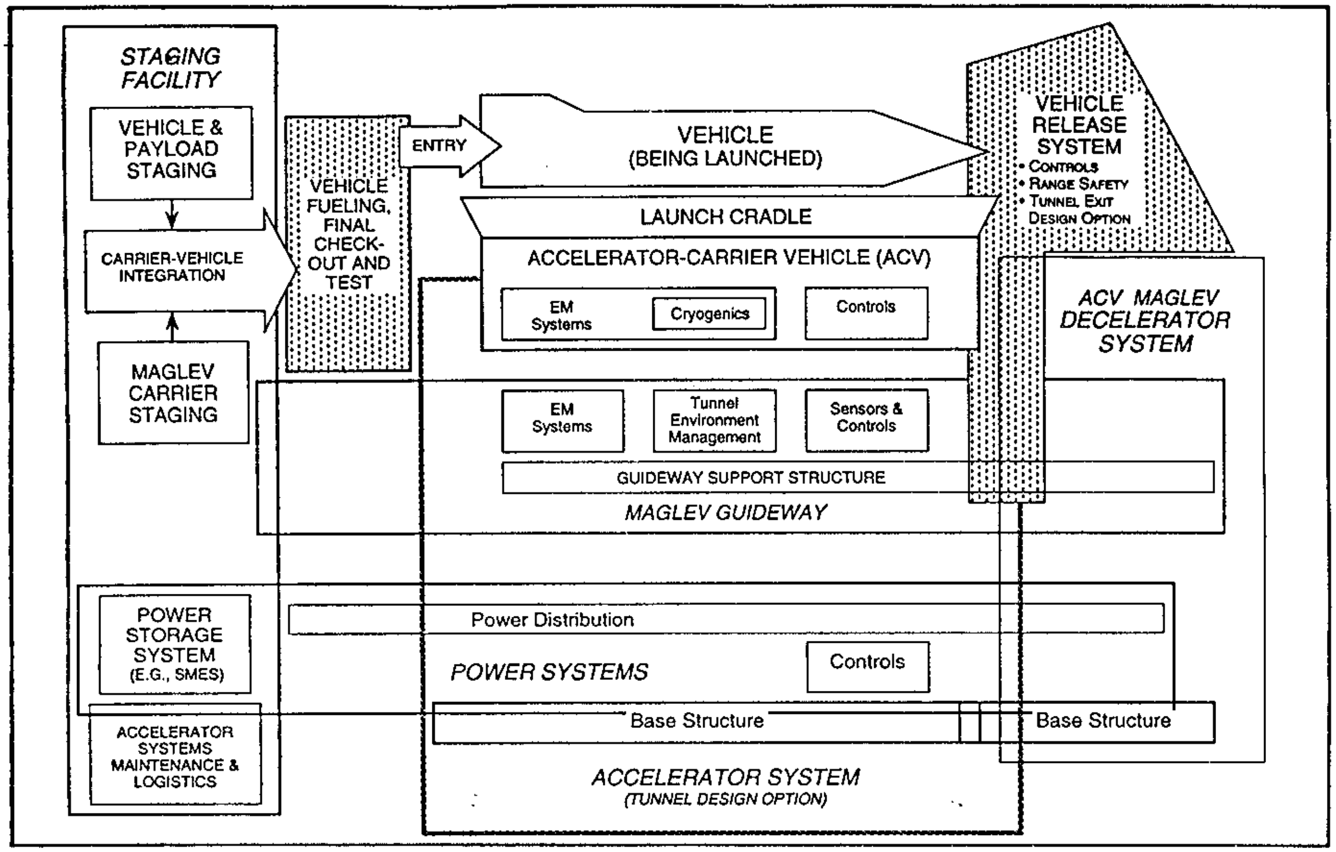

Figure 2 Top-Level Diagram of a large-scale MagLifter system architecture

catapult. However, current technology limits the altitude that can be credibly projected for such a mechanical system to ≤ 1 mile. If future developments allowed significantly larger structures to be built, there would be major performance advantages. (For example, launch at 600 mph from 20,000 to 25,000 feet would provide an enormous performance – and thus cost advantage – over a sea level-based SSTO launcher.)

If a mountain-based tunnel system is used – as is assumed in the reference concept – then the system would include three major elements:

- **The Tunnel** – A highly robust structural support system to altitude is needed. In the reference concept, this is assumed to be a tunnel inside a mountain (accelerator phase, approximately 2.5 miles), and an **External Guideway Support System** on the side of the mountain (decelerator phase, approximately 0.5-1.0 miles).
- **Tunnel Environmental Monitoring and Control Systems** – Within the tunnel, normally an environmentally controlled, oxygen-nitrogen atmosphere will be maintained. Near the end of the catapult, the option will be provided for using a gaseous Helium environment at atmospheric pressure to provide a low density, low drag medium – typically for launches at speeds greater that the speed of sound. [7] The tunnel will require an internal environmental monitoring and climate control system to assure that before each launch the tunnel is clear of foreign objects, that the gas is at pressure, etc.

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[7] The speed of sound in gaseous Helium is in excess of 2000 mph, thus assuring that even at launched velocities higher than the nominal (600 mph) the vehicle in the tunnel will stay well below the transonic regime.

- **Launch / Exit Systems** – Regardless of whether a tunnel is used, a Launch / Exit system will be needed that provides a managed transition from the environment inside the tunnel and on the guideway to free flight in the external environment. Active control of both the vehicle and the accelerator-carrier will be required during the transition.

Power Systems. The three principal issues in MagLifter power and thermal systems are: (1) the storage or generation of power for launch, (2) the management and distribution of power during launch, (3) the dissipation of waste heat from the guideway during and immediately after the launch. Technology options for the MagLifter power system include: direct generation (e.g., using power directly from a power grid developed for the purpose) and intermediate storage of power taken from the local commercial power grid. The former approach might be executed using modular, flexible power generation systems such as gas turbines (a typical gas turbine will produce between 30-50 MW of power.) However, generating the necessary power for a large scale MagLifter system (e.g., on the order of 10 GW for 20 seconds) appears clearly prohibitive. [8]

The latter represents a potentially superior approach, with storage being provided by either a high energy density capacitor system or a superconducting magnetic energy storage (SMES) type system. The reference power system includes two key component systems:

- **Energy Storage System** – A substantial local power supply system is required. In the reference concept, this is assumed to be a Superconducting Magnetic Energy Storage (SMES) system, which charged from the local power grid and then discharged during a launch sequence. [9]
- **Power Management and Distribution** – The power management and distribution (PMAD) system must handle the discharge of the power storage system in approximately 30 seconds of operation.

Thermal Management Systems. Thermal management will also require a significant engineering development. For example, for a large-scale system, launching a rocket SSTO will require on the order of 200 GJ, invested over approximately 60 seconds of the launch sequence. If the maglev system (guideway, ACV, and LSM) are approximately 80% efficient, then the thermal management system must be capable of dissipating approximately 40 GJ (spread over three miles of catapult).

Supporting Systems. In addition, the overall architecture of the launch site including the MagLifter system will require a variety of supporting systems, many of which will depend on the specific operations (and types of vehicles) to be supported. In particular, the supporting systems that will be needed include:

- **Staging Facility(ies)** - A local launched-vehicle and payload staging facility will be required to perform vehicle-carrier integration and related launch vehicle staging (specific to vehicles and payloads) operations. For HRVs, this will include servicing and maintenance facilities for the vehicle following each flight.
- **Operations Control Center** - An operations control center will be required for both staging facility and launch operations. [10]
- **Installation Facilities** - Various facilities will be required for operation of a major launch facility of whatever type, including roads, accommodations for launched vehicle crew (presumably temporary), etc.

Systems Being Launched. The vehicle systems that would be launched by the catapult are the final major elements of a MagLifter-based launch infrastructure. These applicationoptions include small-, moderate- and large- scale systems.

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[8] For a small- to moderate- scale catapult system (e.g., for payloads on the order of 100,000 lbs), power requirements would be approximately 10% of the large system and direct generation might be a more reasonable option.

[9] Clearly, other options to the use of a SMES system exist (such as using a battery of gas turbines for direct power generation during launch). The final choice will be based on the results of studies of life cycle costs, R&D investment values, etc.

[10] By the nature of the concept, MagLifter operations will depend upon rapid turn-around, low-cost (submarine-style) launch operations.

SUMMARY OF POTENTIAL MAGLIFTER APPLICATIONS

Large-Scale Applications

Several varieties of Highly Reusable Vehicles (HRVs) are potential candidates for launch from a MagLifter catapult pad. Each of these would require a large-scale system (e.g., on the order of 3-5 miles of guideway and a launch altitude of 5-15,000 feet), with major supporting infrastructure.

Rocket Single-Stage-to-Orbit Vehicles. One straightforward potential application of a superconducting magnetic levitation catapult is the launch of a rocket single-stage-to-orbit (SSTO) vehicle.

Rocket / Air-Breather SSTO Vehicles. Very similar to the rocket SSTO case described above, the catapult may also be useful in the launch of rocket / air-breathing hybrid SSTO vehicles.

Two-Stage-to-Orbit Vehicles. In addition to SSTO cases described, two-stage-to-orbit (TSTO) vehicles may also be launched on MagLifter. However, in studying these cases, the overall economics of developing and manufacturing three major new systems (the two pieces of the TSTO and MagLifter) seem intuitively prohibitive. Detailed studies of this option are required.

Expendable Launch Vehicles. Although not as prominent as those for reusable, single-stage systems, the advantages of catapult launch for ELVs)are sufficiently interesting to warrant further study.

Intercontinental Transport. In addition to space launch application, MagLifter technology could also be used as a basis for lower-cost hypersonic intercontinental transportation. Such system would entail relatively high launch speeds (Mach 1-3), much higher vehicle structural and thermal system performance than state-of-the-art (SOA) rocket systems (e.g., SSTO concepts). Also, such applications would require deployment of systems in multiple countries for return flights (e.g., in Asia, Europe, South America, and Africa).[11]

Small- to Moderate - Scale Applications

Several potential applications have been identified for smaller-scale MagLifter systems. [12] These include: sounding rockets, small- to moderate- ETO systems, and hypersonic research vehicle launches.

Sounding Rockets. In addition to significantly increasing the performance to LEO of SSTO and ELV systems, MagLifter (perhaps in a smaller focused application) may very well enhance the capabilities of sounding rockets for lower cost microgravity research or upper atmospheric science flights. Preliminary analyses indicate, for example, that the duration of microgravity conditions may be increased by as much as 30 % for a small sounding rocket with a moderate size MagLifter system (with no appreciable increase in costs).

Small- to Moderate- ETO. MagLifter may be useful to enable or enhance performance for small- to moderate size ETO systems of various types. It may also provide lower operating costs than air launch for very small ELVs or TSTO applications.

Hypersonic-Research. A variety of research programs and experimental flight vehicle concepts have been defined for hypersonic vehicle R&D. Small flight experiments, however, will require some initial staging (e.g., air launch or ELV launch) to achieve desired aerodynamic conditions. MagLifter may also be useful in the development of concepts for lower costs hypersonics research vehicle flights.

Other Applications.

Diverse other potential applications exist – near-term and far-term – of maglev catapult technologies. For example, in the near-term applications for Department of Defense test and evaluation programs (e.g., projectile tracking and acquisition system validation and demonstration) may be viable. Conversely, in the very far term, in-space applications of the same technology base could find applications in Lunar surface launch systems (as have been popularized in fiction).

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[11] Although cost and economic analyses are not provided in this paper, it should be noted for comparison that costs of a MagLifter launch site appear comparable to the costs of a major airport.

[12] In almost all cases, these applications could also be performed on a larger MagLifter system, operating with a specialized ACV, etc.

PROJECTED PERFORMANCE ADVANTAGES

Origins of Performance Advantages

Several factors contribute to the performance advantage provided by the MagLifter concept. These include:

- Reduced Rocket Delta-V Requirement. System provides about 300 meters per second of the total velocity change of more than 9000 meters per second needed for ETO transport.
- Reduced Vehicle Drag and Gravity Losses. Reduced pressure at altitude decreases total drag losses. Altitude and velocity vector reduce time to achieve orbit and total gravity losses.
- Improved Engine Performance. Reduced pressure also allows better engine performance (the greatest improvement is achieved for single stage vehicles). This will allow 'tailoring' engines to take advantage of the lower pressure (a study that has not yet done in the analysis presented here.)

Most significant, however, is the timing of these improvements in velocity and reduced losses: at the very beginning of the ascent when each meter of velocity 'costs' the most in terms of propellant 'invested'.

Performance Improvements Summary

The overall performance improvement for Easterly launch is dependent on three factors: altitude, velocity and the angle of the velocity vector. Figure 3 summarizes the results of preliminary analyses illustrating the sensitivity of injected mass performance as a function of altitude for two exit velocities (300 mph and 600 mph). Clearly, in the absence of other factors, higher altitudes and velocity are preferred, while angles above 45 degrees yield minimal performance improvements.

Another factor driving the system to higher exit altitudes is the maximum dynamic pressure experienced by the vehicle (and resulting likely impacts on vehicle structure and dry mass).

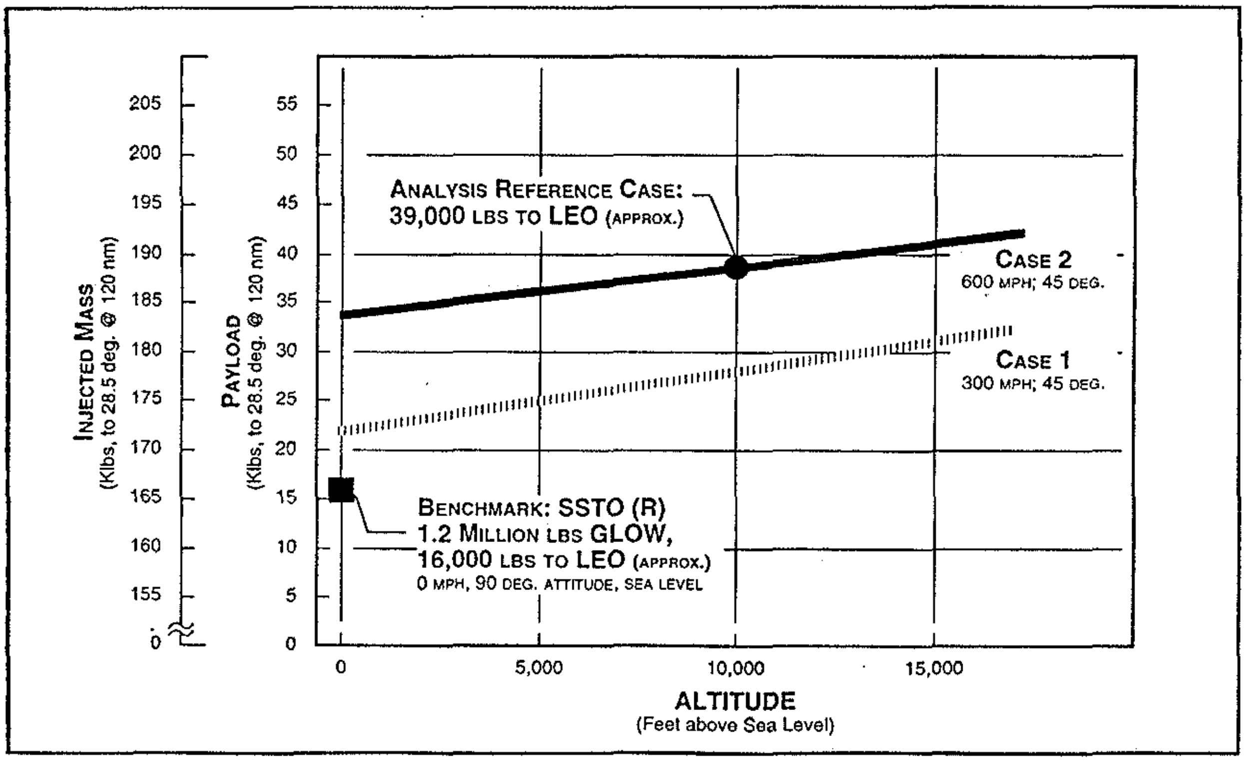

Figure 3 Summary of injected mass performance vs. launch altitude and velocity (simplified analysis)

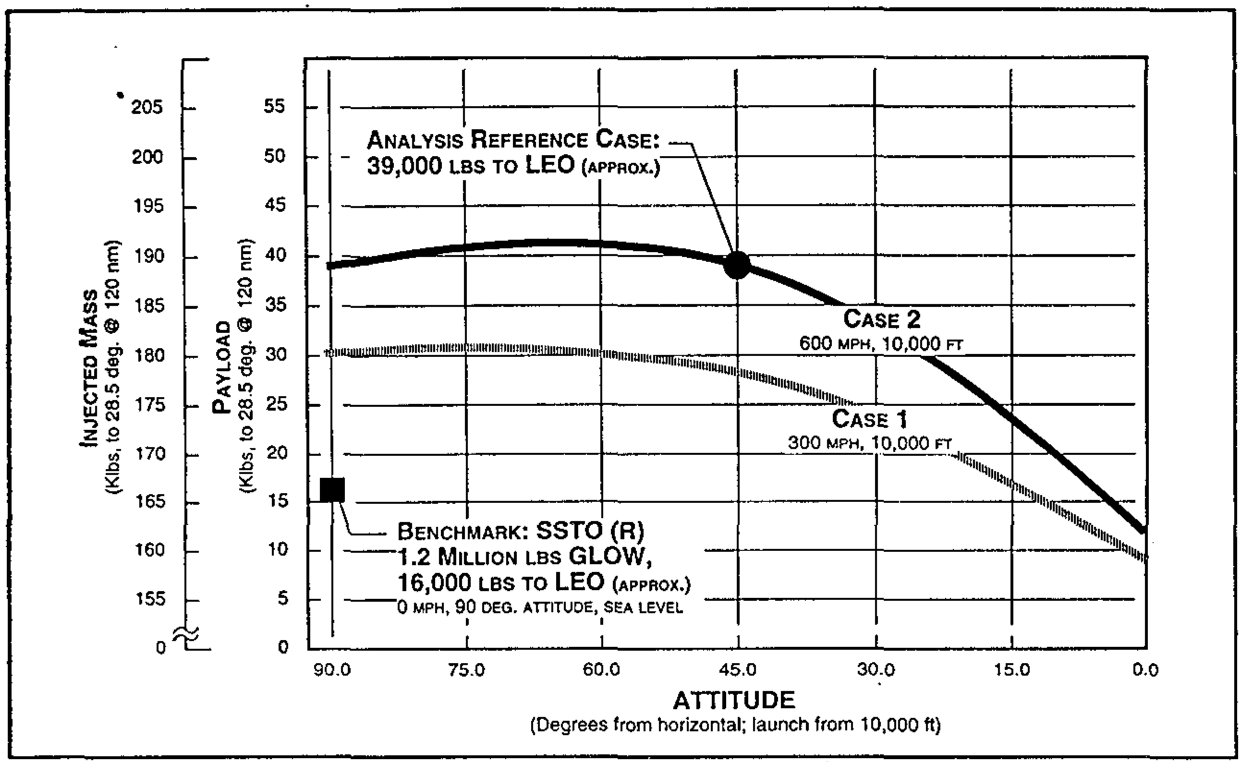

Figure 4 Summary of injected mass performance vs. velocity attitude and velocity (simplified analysis)

Figure 4 provides the results of second series of analyses examining the sensitivity of injected mass performance as function of *velocity vector attitude for two exit velocities* (300 mph and 600 mph).

On this basis of these studies, and in the context of a cursory assessment of the launch sites available (i.e., mountain heights and their availability) the reference case was chosen involving launch from an altitude of 10,000 feet, at a velocity of 600 mph, and an angle of 45 degrees. (This case is discussed in greater detail in the discussion of a SSTO launch application example provided below.)

A third series of analyses was also conducted to evaluate the effects of velocity, altitude and velocity vector angle on the dynamic pressure experienced by the vehicle during ascent following release from the catapult. These results indicate (1) that nominal loads at 500-600 mph are roughly comparable to current space launch environments (e.g., Shuttle launch); (2) that dynamic pressure increases significantly as Mach 1 is approached, and (3) that dynamic loads can be substantially reduced for launch angles of approximately 55 degrees.

The SSTO case described above is the application that has been most thoroughly analyzed thus far. Similar, but somewhat lesser, *advantages have been found for use of the* MagLifter in providing a boost-assist for easterly launch of ELVs. For example, a payload improvement of approximately 80% was found in a very preliminary assessment for a hypothetical ELV (specifically increasing the vehicle's payload from 2000 lbs to 3800 lbs launched to LEO). In a very different case, a preliminary analysis of a very small, two-stage-to-orbit (TSTO) (nominally with air launch), showed no payload advantage for use of MagLifter at 10,000 ft, 600 mph, and 45 degrees angle.[13]

For polar orbit cases, a very cursory analysis suggests that the benefits of using the maglev boost assist may be even greater than for the 28.5 degree case (i.e., perhaps on the order of a 3:1 improvement in SSTO payload delivery to a polar LEO).

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[13] Additional studies are needed to determine if higher altitudes, higher angles, and/or higher velocities change this result.

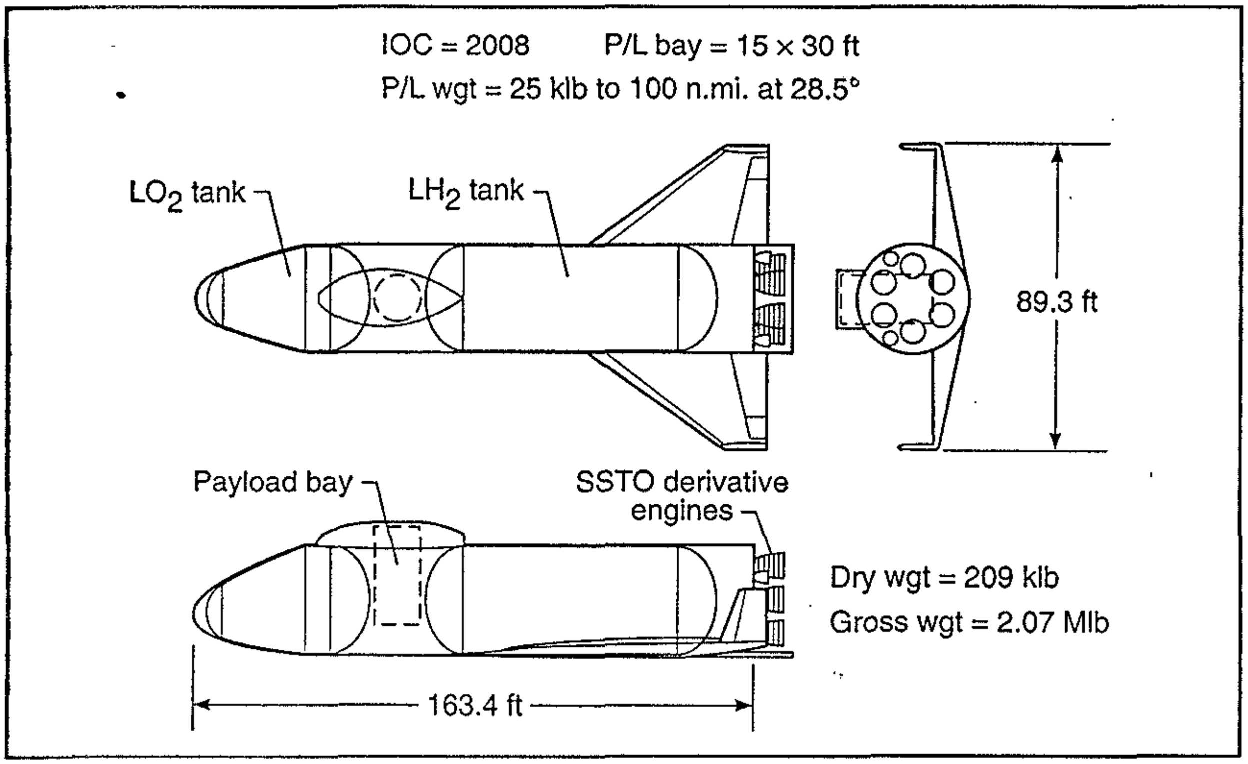

Figure 5 Illustration of reference rocket SSTO vehicle analyzed

APPLICATION EXAMPLE: A ROCKET SSTO USING MAGLIFTER[14]

Although analytically the addition of a MagLifter system to a space launch scenario increases performance for a given vehicle, in actual practice the catapult system would more likely be used to increase design margins and reduce costs while holding performance constant. To illustrate this point, a special application example – a rocket SSTO launched from MagLifter – is presented in the paragraphs that follow, including: (1) a brief description of the reference vehicle, (2) potential impacts on the reference vehicle as a result of addition MagLifter to the infrastructure, and (3) a description of a top-level hypothetical launch sequence.

Reference Vehicle

The reference vehicle for this analysis represented a relatively moderate projection beyond the state-of-the-art. The vehicle was scoped to launch 25,000 lbs to LEO, using 6 Space Shuttle Main Engine (SSME) class engines and LOX-Hydrogen propellants.

The reference vehicle dry mass was 209,000 lbs, with a gross lift off weight (GLOW) of 2.07 Mlbs.[15] Figure 5 provides an illustration of this reference vehicle, along with key parameters.

Vehicle Impacts

For the launch of 25,000 pounds to LEO, a preliminary analysis of the addition of MagLifter (for the reference case of 10,000 feet, 600 mph, 45 degrees), results in a 25 % reduction in vehicle dry mass and a 33 % reduction in engine mass (assuming use of a Space Shuttle Main Engine, SSME, class propulsion system). Figure 6 depicts the potential change in size that might be possible for an conventional SSTO (at sea level), versus anSSTO (with the same technology base) designed for launch from an appropriately sized MagLifter launch pad.[16]

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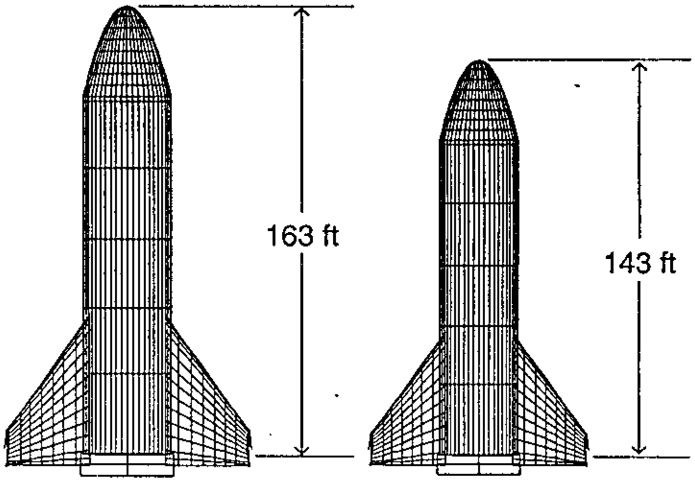
[14] The case presented here was developed by the Vehicle Analysis Branch at NASA LaRC.

[15] This vehicle is somewhat larger than that in other aspects of the analysis presented here (which launched16,000 lbs to LEO without MagLifter and had a GLOW of approximately 1.2 Mlbs).

[16] The importance of this change will become apparent when cost and economic analyses are done, since many cost factors vary with vehicle dry mass.



Launch: Altitude, ft	0	10,000
Velocity, ft/sec	0	880
Attitude, deg	90	45
Gross weight, lb	2,070,000	1,350,000
Dry weight, lb	209,000	156,000
Number of engines	6	4

Figure 6 Illustration of potential size changes in a rocket SSTO using MagLifter

Nominal Launch Sequence

A nominal launch sequence for the rocket SSTO-class MagLifter system described here (and shown inf Figure !) might consist of the following events:

(1) At T-2 hrs, the ACV with vehicle to be launched and payload leaves the staging facility on the initial section of the guideway and is transported to the propellant loading site for fueling.

(2) At T = 0 seconds, following fueling and final check-out, the ACV and vehicle to be launched are disconnected from ground support equipment and travel on the guideway to into the MagLifter tunnel (reference case).

(3) At T + 10 seconds, the vehicle and ACV slowly begin accelerating . This acceleration lasts for approximately 30 seconds, at the end of which time the ascent phase of the sequence begins.

(4) At T + 40 seconds, the vehicle and carrier begin ascending (at a nominal final angle of 45 - 55 degrees from the horizontal), and at increased acceleration, reaching an altitude of approximately 7000 feet and a velocity of 450 mph after 10 seconds

(4) At T + 50 seconds, final check out and test of the vehicle in motion begins. The engines of the vehicle are started to idle and checked out; if they perform to specification, a 'go' decision is made, and acceleration continues.

(5) At T + 58 seconds, a velocity of approximately 650 mph is reached. The cradle on the ACV releases the vehicle being launched, which separates (engines remaining at idle). The ACV begins to decelerate.

(6) At T + 60 seconds, the vehicle leaves the end of the guideway at 600 mph and at an angle of 45-55 degrees, and an altitude of 10,000 feet (nominal). The vehicle's engines power up and it begins its ascent to orbit. The ACV continues to decelerate, leaving the tunnel (in the reference case) and exiting on the external section of guideway.

Parameter	Gas Gun	Rail Gun	Coil Gun	MagLifter
Exit Velocity (mph)	19000	12000	13000	**≥ 600 (varying)**
Acceleration (gravities)	2000	5000	2500	**≤ 3 (varying)**
Payload (kilo-pounds)	>20	< 3	< 3	**1000 (varying)**

Table 1 Comparison of MagLifter to 'Other' Gun Concepts

COMPARISON OF PERFORMANCE TO 'OTHER' GUN CONCEPTS

Although MagLifter is not properly a 'gun', a comparison is useful by indicating how dramatically thi catapult concept differs from 'other' types of gun launch concepts . MagLifter can launch much larger payloads, with lower accelerations during launch and closer ties to existing space launch and ground transportation technologies. For example, a typical advanced gun concept, the light gas gun, would in an operational system be capable of 'firing' only 100 kg-class payloads to LEO, and only by subjecting them to 1000 G-class accelerations at launch. Table 1 summarizes some of the relevant characteristics for several gun concepts (in projected operational systems) and compares them to MagLifter.

MagLifter – plus an HRV – could provide a far broader range of payload performance, with much more benign environmental conditions.

MAGLIFTER TECHNOLOGY

Technology Challenges

The major research and engineering development challenges associated with investigating the potential of maglev technologies for space launch applications include both core areas (where technology research is completed and/or capabilities exist that could be applied 'as is'), and opportuntities (where further advances could make a significant cost or performance difference).

Core areas, such as:

- the large mass EM levitation system
- the high energy/high acceleration EM propulsion system
- developing a low-cost, highly reliability ACV system, including the payload cradle system
- extremely high-power power systems (storage and PMAD)
- high-load thermal management systems
- high reliability and low-cost range and site safety systems
- low-cost operations

And High-Leverage technology opportunities, such as:

- high temperature superconducting materials and EM systems
- low-cost tunnel systems
- low-cost maglev guideway systems (structure, EM systems, construction, repair and maintenance)

In summary, although the parameters associated with MagLifter are aggressive (600+ mph speeds, 3-G accelerations, large payloads, etc.), at the present level of definition, no major issues have been identified that might be technological 'show-stoppers' for the concept.

Dual-Use Technology Applications

There are diverse opportunities for dual-use applications of the technologies required for MagLifter R&D and eventual development.

Advanced Electromagnetic Systems. At a subsystem level, MagLifter development could drive R&D and industrialization of various advanced EM systems, including high-power level energy storage (e.g., SMES) and PMAD systems, superconductors and high temperature superconductors.

Ground Maglev Transportation Systems. At a system level, many or most of the technologies needed for the implementation of a MagLifter launch pad are also needed for the development and deployment of a 'leap-frog' maglev ground transportation system infrastructure.

SELECTED ISSUES AND AREAS FOR ADDITIONAL STUDY

Several options in the system design require further study to resolve issues that have arisen in preliminary analyses. Also, several important areas need first-order examinations.

Performance Issues[17]

Effect of Off-Inclination Launches. Initial studies of propulsive vehicle maneuvers to adjust from a due Easterly launch direction on the catapult to other orbital inclinations indicate minimal losses in injected mass system performance. For example, for a due East launch from a 28.5 degree latitude site to a 51.6 degree inclination orbit at 220 nm altitude, the *injected mass fell by less than 3%. The* corresponding drop in payload mass was approximately 15%. The effects of these maneuvers are modest because of the relatively low starting velocity of the vehicle being launched.

Effect of Launch Site Latitude. A preliminary analysis of the effect of changing launch site latitude has been conducted. The effect of translating the MagLifter launch site from approximately 30 degree latitude to the Equator is an increase in injected mass of approximately 5%, The corresponding improvement in payload is approximately 20% (for due East launch). Clearly, in terms of payload launched to LEO, an optimal MagLifter launch site would be a 10-15,000 ft peak near the equator. The reduction in payload, however, appears to be acceptable at launch latitudes in the U.S.

Areas for Additional Study

Tunnel System. As discussed previously, the use of a tunnel or other approach to basing and protecting the maglev guideway system is a major design trade issue to be considered. Top-level arguments in favor of a tunnel approach include protection from weather (a significant issue at high altitudes) and for security. Conversely, wall effects during acceleration and launch failure and risk scenarios must be assessed as potential arguments against this approach.

Cost Estimation. A detailed cost analysis is not being presented in this paper. However, preliminary analyses have been developed for purposes of comparative assessment of options. These studies indicate that, depending on the size of the system constructed, the MagLifter would range in cost from approximately $0.2B for a small- to moderate- scale system (e.g., for a 100 klbs vehicle), to $2B for a large-scale system (e.g., for a 1-2 Mlbs vehicle). In addition, costs of supporting infrastructure must be evaluated (e.g., launch vehicle and payload processing, operations control center, etc.).

In addition, MagLifter catapult operations costs must be analyzed, including: (1) labor, (2) consumables (including power and potentially gaseous Helium), (3) expendable systems (such *as the 'burstable' membrane at the tunnel exit, if* one is used), and (4) refurbishment and maintenance of tunnel, guideway and ACV systems as required between launches.

Economic Analysis. A preliminary analysis of potential MagLifter resource-streams is needed. This analysis should be grounded in initial estimates for MagLifter development costs, and should be directed at enabling a notional sense *of how this system might integrate into plans for* space launch and ETO transportation. A variety of inputs will be needed in the development of such an analysis, including:

(1) For ETO studies, annual launch requirements must begin with the NASA Civil Needs Data Base (CNDB). As excursions from the baseline, additional launches, such as new LEO telecommunications satellite

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[17] In the cases listed below, the vehicle in question was a reference LOX-Hydrogen rocket SSTO vehicle with a 1.2 Mlbs GLOW unless otherwise stated; conclusions pertain to projected changes in injected mass.

constellations should be assessed for inclusion.[18]

(2) HRV and other vehicle costs used in the analysis should be developed from a credible, independent source.

(3) MagLifter system development and operations costs must be estimated with significant uncertainly to allow for the low level of maturity in the concept.

(4) Many staging facility costs will depend on the number and types of vehicles and payloads to be processed and details of operational scenarios. A consistent approach to this area is needed.

(5) The overall economics analysis should consider financing alternatives for the MagLifter infrastructure and launch vehicles.

Finally, a number of cases must be analyzed, representing various alternative infrastructure developments and vehicles over an extended period (e.g., 1995-2024).

Market Analysis. Market factors must be examined carefully. The recent CSTS analysis suggests that if overall ETO launch costs were reduced to \$ 600 per pound that the mass-to-orbit market could almost triple compared to current annual levels. However, their analysis also indicates that an additional reduction of 33% (to \$ 400 per pound) could stimulate massive market growth.

Comparisons to Competing Similar Concepts. An immense number of space launch concepts have been studied during the past half century. Although a smaller number, there also are a variety of alternate approaches that involve the same basic principles as the MagLifter; i.e., adding initial altitude or velocity to a projectile or vehicle. For example, the operational Pegasus system developed by the Orbital Sciences Corporation involves air launch as an assist to ETO transport.

Comparison to Gun Concepts. Additional comparisons to proper gun concepts are also needed. It may well be that synergism will be found between the infrastructure needed for MagLifter and that needed for many types of guns (e.g., power supplies, physical infrastructure such as the tunnel used in the reference concept).

SUMMARY

This paper has provided a preliminary discussion of the MagLifter concept. Many topics have been raised, but not resolved – ranging from diverse vehicle mission analyses, to system basing and range safety considerations; from system functional studies to identifying technology development challenges.

It is clear that a revolutionary 'launch pad' such as the MagLifter catapult makes no sense without new, tailored space launch vehicles to use it. Conversely, if developments in low-cost vehicles are fully successful, no new launch pad technology may be needed. However, based on preliminary analyses, the application of maglev to space launch appears to have considerable promise across a wide variety of applications, ranging from ETO transportation (HRV and ELV), hypersonics research, sounding rocket launches, and more futuristic concepts (such as intercontinental hypersonic transports). By providing an initial, 'free' delta-velocity, MagLifter may represent 'insurance' for other developing space launch systems concepts. At the same time, maglev and advanced, high power electromagnetic systems have diverse potential terrestrial dual-use commercial applications.

ACKNOWLEDGMENTS

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Special thanks are due to Mr. Vince Dauro of MSFC for his efforts in conducting innumerable mission performance analyses and to Mr. Charles Eldred and the staff of the Vehicle Analysis Branch at LaRC for their analysis of the SSTO option.

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[18] The recent Commercial Space Transportation Study (CSTS) Executive Summary provides a potential roadmap for this analysis.

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GLOSSARY OF ACRONYMS

ACV	Accelerator-Carrier Vehicle
AFB	Air Force Base
ALS	Advanced Launch System
BMDO	Ballistic Missile Defense Organization
CNDB	Civil Needs Data Base
CSTS	Commercial Space Transportation Study
DOD	Department of Defense
DOT	Department of Transportation
EDS	Electrodynamic Suspension
EM	Electromagnetic
EMS	EM Suspension
ETO	Earth-to-Orbit
fps	feet per second
FRA	Federal Railroad Administration
G	Gravities (of acceleration)
GJ	Gigajoules
GLOW	Gross Lift-Off Weight
GW	Gigawatts
HRV	Highly Reusable Vehicle
klbs	Thousands of Pounds
LaRC	Langley Research Center
lbs	Pounds
LEO	Low Earth Orbit
LMATO	Linear Motor Assisted Take-Off
LSM	Linear Synchronous Motor
M	Millions
Maglev	Magnetic Levitation
MJ	Megajoules
Mlbs	Millions of Pounds
mph	miles per hour
MSFC	(NASA) Marshall Space Flight Center
MW	Megawatts
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NLS	National Launch System
NMI	National Maglev Initiative
O&M	Operations and Maintenance
PMAD	Power Management and Distribution
R&D	Research and Development
SDIO	Strategic Defense Initiative Office
SMES	Superconducting Magnetic Energy Storage
SMS	Superconducting Magnetic Systems
SNTP	Space Nuclear Thermal Propulsion
SSME	Space Shuttle Main Engine
SSTO	Single-Stage-to-Orbit
TSTO	Two-Stage-to-Orbit
USAF	U.S. Air Force