# Superconducting Magnets for Maglifter Launch Assist Sleds

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*Abstract*—**The Maglifter is an electromagnetic catapult being considered by NASA to reduce the cost of lifting a payload into space. The system would accelerate a vehicle of up to 590 tonnes to a final velocity of 268 m/s at an acceleration of 2 g. Superconducting coils are considered for levitation because they permit track-to-vehicle clearances of more than 95 mm. The high clearances reduce tolerances and maintenance costs, and allow a system with permanently deployed wheels for take- off and emergency landing. Cable-in-conduit conductors (CICC) were selected because of their high electrical and mechanical strength, as well as high energy margin for stability. The selected coil shape is a pair of racetrack coils forming a module with four modules on a sled. The superconducting levitation modules weigh about 4% of the gross lift off weight and are capable of achieving lift off at about 20 m/s. The maximum magnetic drag power is negligible compared to the power required for acceleration.**

*Index Terms*— **electromagnetic catapult, maglev, maglifter, magnetic levitation , superconducting magnets**

## INTRODUCTION

MAGLIFTER [1], an electromagnetic (em) launch assist catapult considered as part of a NASA reusable launch vehicle system, has the potential for significantly lowering the recurrent cost of cargo delivery to low earth orbits and to improve launch reliability [2]. In this concept, a reusable space vehicle is mounted on a carrier sled, which is magnetically levitated on a horizontal guideway and accelerated with em propulsion to a speed of about 1000 kilometers per hour. Towards the end of the catapult, the engines of the vehicle are fired to propel it into orbit. The goal is to handle vehicle/sled weights up to about 600 tonnes.

The use of superconducting magnets has been proposed as the primary suspension for this launch assist catapult. The principle is that a moving DC magnet will induce eddy currents in a stationary electrically conducting guideway with a polarity that will always tend to levitate the "flux-conserving" magnets. This technique of magnetic levitation is "passive" and "repulsive". Magnetic suspensions have previously been proposed using continuous, conducting sheet guideways, e.g. [3], or guideways with discrete coil systems. The latter have been demonstrated in full-scale linear motor passenger vehicles, e.g. [4].

Guideways with discrete coil systems necessarily induce time varying forces on the vehicle levitation coils whereas a sheet guideway produces forces on the coils that are steady state. The sheet guideway, therefore, avoids this major source of induced vibrations and was selected for this study.

Discrete coil guideways can result in electromagnetic lift to drag ratios that are much higher than those for sheet guideways. However, this is a marginal benefit in a public transport system and unimportant for Maglifter, where the thrust required is dominated by acceleration and em drag power is insignificant compared to the power for acceleration.

A levitating magnet system was sized for a maximum vehicle/sled weight of 590 tonnes, with an acceleration of 2g, and end speed of 1000 km/hr. The coil current could be adjusted before a shot to accommodate weight variations for a given vehicle, or shorter coils could be used on a shorter sled for a sled/vehicle of significantly less weight. A specific winding pack and cable-in-conduit-conductor (CICC) preliminary design was developed.

## BOGIE CONFIGURATION

Superconducting coils will be located in two bogies, one at each end of a sled. Fig. 1 shows a section through a vehicle on a sled over a guideway and an isometric of the coils in one bogie.

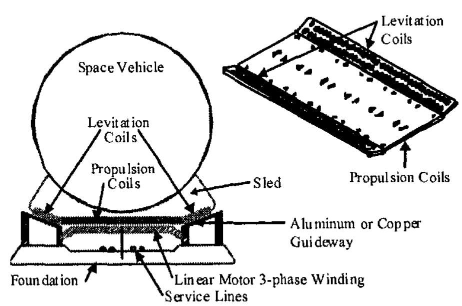


Fig. 1. Cross-section of vehicle, sled, bogie and guideway, with an isometric of the coils in one bogie.

In a bogie, two long racetrack coils with opposite polarity are located on each side of a set of propulsion coils in the center.

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The propulsion coils were not part of this study, but are expected to be superconducting and interact with the field produced by a 3 phase linear synchronous motor winding in the center of the guideway to transfer the necessary thrust to the vehicle. The field from the racetrack levitation coils induces eddy currents in a copper or aluminum sheet that is part of the guideway. They are mounted at an angle to provide lateral stability. At zero speed there is no eddy current induced in the guideway and, in turn, no lift, hence the sled rides on wheels at low speed. These wheels will maintain the vehicle at a constant height above the guideway until the speed increases to the point where the em lift is sufficient to raise the sled and eliminate wheel contact.

## LIFT, DRAG AND SIZE OF THE LIFT COILS

Each racetrack coil has a winding centerline trace of about 0.4 m x 9.6 m in a plane parallel to the guideway. A pair of racetrack coils comprise one module and are mounted co-planar in a cryostat with envelope dimensions parallel to the guideway of about 1.08 m x 10.6 m. The average normal pressure under a levitation coil is about 0.2 MPa.

Fig. 2 shows levitation performance for a 590 tonne vehicle/sled as a function of speed for a 2 cm thick aluminum sheet guideway. The ordinate, H, is the distance from the center of the coil cross-section to the surface of the guideway. The space required for coil, structure and cryostat is 6 cm, so the clearance between guideway and cryostat is (H- 6 cm). Curves are shown for constant height provided by wheels and constant lift provided by the levitation coils. In this case, complete magnetic levitation occurs above a speed of about 50 m/s and the full speed guideway clearance is 9.5 cm. The magnetic lift provided is approximately proportional to speed at low speed and reaches the full load capacity at the lift off point.

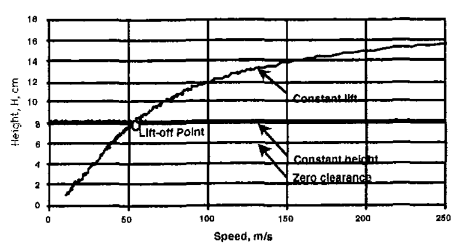


Fig. 2. Height, H, for the levitation module cryostat relative to the guideway vs speed for a 590 tonne vehicle, a 2 cm Al guideway and $3.2 \times 10^5$ ampere turns per lift coil. Clearance is (H-6 cm).

The em lift to drag ratio is proportional to speed, achieves a value of 70 at 250 m/s, and is very weakly dependent on H. The em drag for a vehicle is given in Fig. 3. At low speed, before lift off, the drag is determined by a constant height condition because of the wheels. After lift off, the drag is determined by a constant lift condition of 590 tonnes. The maximum em drag occurs before lift off and is about $4.1 \times 10^5$ N. At high speed the em drag is about $8 \times 10^4$ N. These values are small compared with the $1.16 \times 10^7$ N required for accelerating the vehicle at 2 g, hence, there is essentially no benefit to increasing the cost (and decreasing the reliability) of the guideway to include a configuration such as discrete coils to improve the em lift/drag ratio.

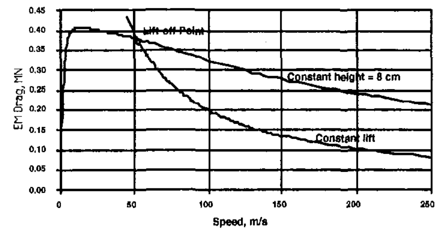


Fig. 3. EM drag due to interaction of 4 levitation modules with a 2 cm Al guideway for a constant height before lift off and constant lift of 590 tonnes after lift off.

The relatively high lift off speed shown in Fig. 2 and Fig. 3, can be decreased by increasing the conductivity of the guideway or by increasing the ampere turns in the lift coils. The ability to adjust the ampere turn level before a shot also offers the possibility to compensate for payload variations and maintain specified operating clearances.

Fig. 4 shows typical performance as a function of velocity for a 2 cm copper guideway and for the Maglifter levitation coil geometry, with a variation in ampere turns of about +/-10%. It indicates that the operating clearance can be adjusted by changing the ampere turns. It also shows that the lift off speed will be lowered to about 20 m/s for this coil set with a copper guideway.

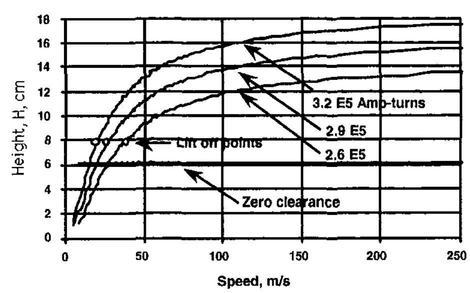


Fig. 4. Height, H, for the levitation module cryostat relative to the guideway vs speed for a 2 cm Cu guideway and selected lift coil ampere turn levels for a constant lift of 590 tonnes. Clearance is (H-6 cm).

The em lift to drag ratio for the 2 cm copper guideway can again be shown to be proportional to speed and reaches 148 at 250 m/s. The em drag for this case is shown in Fig. 5. At low speed the maximum drag is $3.3 \times 10^5$ N and occurs at about 5 m/s. The em drag is again trivial compared to the force and power required for acceleration at 2 g.

It is clear that there may be some advantage to tailoring the guideway material or thickness over the length of the guideway, possibly using copper in the low speed section and aluminum or thinner copper sheets in the high speed section. The low speed drag peak could be removed completely by not having a conducting sheet in this section and tailoring the thickness as the lift off point is approached. It can also be shown that the lift off speed can be adjusted by changing the lift coil geometry, e.g. [7], so there is considerable flexibility on this issue from the design standpoint.

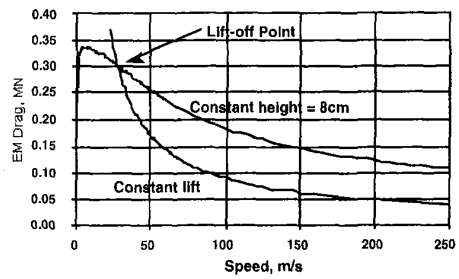


Fig. 5. Electromagnetic drag for a 590 tonne vehicle due to the interaction of the levitation coils (2.9 x $10^5$ At per coil) with a 2 cm Cu guideway.

## WINDING PACK AND CONDUCTOR

The characteristics of a two coil lift module are outlined in Table I. The design is based on a cable in conduit conductor which is pancake wound. The outer dimensions of the insulated conduit are 5 mm x 5 mm, which results in 3 double pancakes with 16 turns per pancake. The conduit wall thickness is about 0.4 mm.

TABLE I
CHARACTERISTICS OF A TWO COIL LIFT MODULE

| Item | Units | Value |
|---|---|---|
| Turns per coil | ---- | 96 |
| Operating Current | ampere | 2983 |
| Max field | T | 2.4 |
| Stored energy | MJ | 2.1 |
| Weight of 2 coils and cryostat | tonnes | 6.0 |

Preliminary analyses of the winding pack indicate that the bulk of the lift load distribution at high speed occurs along the two long legs of the racetrack coils that are near each other in a given module. Stress analyses were performed to size structure to transmit loads from coil to the cryostat outer boundary and to determine that stresses in the conductor conduit were acceptable.

The superconducting cable design considered trade-offs for:

-NbTi vs $Nb_3Sn$
-impact of copper/non-copper ratio in composite wires
-the use all composite wires vs ratios of pure copper wires to composite wires of 1/3 and 2/3

The conductor chacteristics based on the preliminary optimization are given in Table II. In general, $Nb_3Sn$ will always have higher performance than NbTi and a cable with all composite wires will usually have higher performance than combinations of composite and pure copper wires. However, since $Nb_3Sn$ is also more expensive than NbTi and composite superconductor wires are much more expensive than pure copper wires, there should be a large performance difference in order to justify the additional cost. It would be unusual to use $Nb_3Sn$ at fields of this low level; however, the cost of the conductor relative to the system is very small and $Nb_3Sn$ can provide an order of magnitude more energy absorption capacity for AC losses and disturbances. This can translate into higher reliability and may justify its use.

The conductor design is expected to require further study when the disturbance spectrum and corresponding AC losses are better defined.

TABLE II
PRELIMINARY NbTi AND $Nb_3Sn$ CONDUCTOR DESIGNS

| Item | Units | NbTi | Nb3Sn |
|---|---|---|---|
| Wire diameter | mm | 0.71 | 0.71 |
| No. of composite wires in cable | --- | 27 | 18 |
| No. of Cu wires in cable | MJ | 0 | 9 |
| Cu/non-Cu | --- | 6:1 | 4.5:1 |
| Helium area in cable | $mm^2$ | 6.9 | 6.9 |

## LEVITATION COIL GEOMETRY

In any levitation system using a sheet guideway, the lift capability of a given module can be shown to be proportional to the square of the ampere-turns in the coils. This allows a given superconducting system to be adjusted before a mission for a large weight variation, maintaining the same operating gap. It also allows for a new system to be designed for a multiple of the weight, by small changes in coil cross-section (e.g., twice the weight would require only a 41% increase in ampere turns or, equivalently, a 20% increase in linear dimensions of the coil cross-section at the same current density). Alternatively, for the specific long racetrack coil design in this paper, the lift at a given ampere-turn level is essentially proportional to coil length. Hence, a prototype demonstration system at 100 tonnes could use modules of essentially the same cross section and roughly 1.6 m long.

## SUPERCONDUCTING COILS VS PERMANENT MAGNETS

It is possible to use permanent magnets (PM) for levitation modules. There is a significant gain in lift to weight ratio for a given amount of material if they are used in a Halbach array [5] which increases the field dramatically on the side of the array nearest the guideway. The Halbach array can also be done with wound coils [6] and a first order comparison of a PM module with a superconducting module can be made as follows.

It is necessary to consider the limited ability of a PM to increase the equivalent ampere turns that can be provided locally. For example, the superconducting coils with cryostats considered earlier are about 0.25 m thick and provide about 3x$10^5$ ampere turns around the boundary of one coil. A PM with a residual induction, Br, of about 1.25 T, can provide the equivalent around its boundary of about 1 x $10^6$ ampere per meter of height. Therefore, a PM height of 0.3 m would provide about 3 x $10^5$ ampere turns. However, the PM would be much heavier than the superconducting coils with cryostats with the same footprint area because of the difference in average mass density within the envelope volume.

Fig. 6 shows lift to weight ratio as a function of clearance for several values of Br assuming the use of a Halbach array in either a PM or a wound superconducting magnet. An optimized value for the array thickness and wavelength relative to the clearance was also used following Post [5]. If we assume, with considerable penalty to the superconductng magnet, that the average mass density for a superconducting magnet is the same as that of a PM module, then an approximate comparison of performance for the two types of modules can be made. PM arrays are limited to Br = 1.4 or less and, because of this, their performance in terms of maximum possible lift per unit weight of array degrades rapidly as clearance increases. Superconducting coils can be expected to operate at Br equivalent fields that exceed 1.4 T and are, therefore, much more appropriate for large clearance operation. For example, Figure 6 shows that a permanent magnet module (Br=1.4 T) and Lift/Weight ratio of 30 could operate at a clearance of 4 cm. For the same Lift/Weight ratio of 30, a superconducting module with a Br=3 T could operate with a y value of 20 cm. The latter must be decreased for the distance from winding surface to surface of cryostat which could be about 5 cm so the actual clearance is 15 cm. The latter is still a factor of almost 4 larger than the clearance with the permanent magnet module.

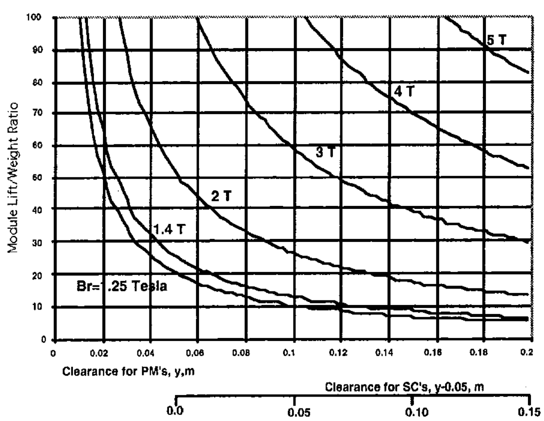


Fig. 6. Approximate lift to weight ratios vs clearance to the guideway for permanent magnets and superconducting coils. Halbach array used for PM or for wound SC coils. PM is limited to Br <1.4 T.

For a desired clearance of, for example, 10 cm, Fig. 6 shows that the Lift/Wt ratio for a permanent magnet system would be about 13 for a Br=1.4 T. If we add 5 cm to the required clearance of 10 cm to allow for a superconducting magnet cryostat, then a superconducting magnet system at 3 T (and y=15 cm) would have a Lift/Wt ratio of 39. The Lift/Wt ratio is better for the SC magnet system by a factor of 3.

Results in Fig. 6 are approximate and further studies should be done to explore the impact of adjusting the assumed weight density of the SC module to a lower value, and relating the operating field level selected to conductor performance. Cryogen support equipment is not included. This is acceptable in the case of Maglifter where the cryogen support equipment would not be mounted on the sled.

## CONCLUSIONS

A 590 tonne vehicle can be levitated easily by superconducting racetrack coils in a 2 bogie sled with 4 levitation modules. The vehicle and magnet weights are given in Table III.

TABLE III
VEHICLE AND MAGNET WEIGHTS

| Item | Units | Value |
|---|---|---|
| Levitated Load | tonnes | 590 |
| Magnets (one module) | tonnes | 0.93 |
| Magnets (system) | tonnes | 3.73 |
| Magnets + cryostats (one module) | tonnes | 6.0 |
| Magnets + cryostats (system) | tonnes | 24.0 |

The superconducting magnets can lift over 150 times their own weight without being overstressed. The magnet/cryostat systems, including the windings, helium can, vacuum vessel, radiation shields, cold-warm supports, and leads, can lift 25 times their own weight. These ratios can be improved by further optimization.

The maximum em drag with a sheet guideway occurs before lift off and reduces as the speed increases. The values are small compared with the thrust required for accelerating the vehicle at 2 g, hence, there is essentially no benefit to using discrete coils in the guideway for levitation.

The lift off speed can be decreased by increasing the conductivity of the guideway, by increasing the ampere turns in the lift coils, or by changing the coil geometry [7]. The ability to adjust the ampere-turn level before a shot also offers the possibility to compensate for payload variations and maintain specified operating clearances. A similar adjustment with a PM system would require adding or removing PM sections.

Because the lift capability of a module is proportional to the square of the ampere-turns in the coils, a new system can be designed for a multiple of the weight, by small changes in coil cross-section. Alternatively, for the Maglifter, long racetrack coil design, the lift at a given ampere-turn level is essentially proportional to coil length. Therefore, the racetrack design is universal in that it can provide for large variations in lift by changing ampere-turns or designing for a different length.

## REFERENCES


[1] J.R. Olds and P.X. Bellini, "Argus, a highly reusable SSTO rocket-based combined cycle launch vehicle with maglifter launch assist," *AIAA 8th International Space Planes and Hypersonic Systems and Technologies Conference*, Norfolk, VA, April, 1998.

[2] J.W. Haney, et al, "Highly reusable space transportation (HRST) advanced concepts study," Final Report, Cont no. NAS1-19243; Task 25, Rockwell Project: 43120, 30 Nov., 1995.

[3] H. Kolm and R. Thornton, "Electromagnetic flight," *Scientific American*, vol. 229, no. 4, pg. 17, October, 1973.

[4] H Tsuruga et al, "Superconducting magnetic levitation transportation systems on the yamanashi maglev test line," *Hitachi Review*, vol. 46, pg. 89, No. 2, 1997.

[5] R.F. Post and D.D. Ryutov, "The inductrack approach to magnetic levitation," *Proc of the MAGLEV2000*, RiodeJaneiro, p15, June, 2000.

[6] D.L. Trumper, W. Kim, and M.E. Williams, "Magnetic arrays," US Patent 5631618, May 20, 1997.

[7] R.J. Thome, A. Radovinsky & B. Montgomery, "EDS levitation and guidance using sheet guideways," *Proc of the MAGLEV2000*, RiodeJaneiro, pg. 236, June, 2000.