SUPERCONDUCTING ELECTROMAGNETIC SUSPENSION (EMS) SYSTEM FOR GRUMMAN MAGLEV CONCEPT[*]

p. 15

Swarn S. Kalsi
Grumman Corporation
Bethpage, New York

SUMMARY

Maglev vehicles normally employ one of the two types of Maglev suspension systems: Electrodynamic Suspension (EDS) and Electromagnetic Suspension (EMS). The EDS system provides suspension by a repulsive force between the magnets on the vehicle and the reaction magnets (or conductive metal sheets) on the guideway. On the other hand, the EMS system is based on an attractive force between electromagnets on the vehicle and iron rails on the track. Grumman has adopted the EMS for its Maglev. The Grumman Maglev system consists of superconducting C-iron cored magnets on the vehicle. They are attracted to iron rails mounted on the underside of the guideway. The magnets and rails are oriented in an inverted 'V' configuration in such a manner that the attractive force vectors between the magnets and the rails act through the center of gravity of the vehicle. These magnets simultaneously perform functions of vehicle levitation and propulsion. They are powered by NbTi superconducting coils operating at 4.2K. An electromagnet consists of a C-core, a superconducting (SC) coil on the back leg of the C-core and a normal control coil on each leg of the C-core. The SC coil provides the nominal lifting capability and the normal coils handle rapid variations in load with respect to the nominal value. The EMS system provides levitation at all speeds but the EDS only starts to levitate the vehicle at speeds above ~ 60 m.p.h. Below this speed, the vehicle must be supported by wheels. In an EDS system, SC magnets are shielded from the harmonics of propulsion winding by an aluminum shield. The thickness of this shield is inversely proportional to the square-root of the frequency. At very low speeds, the frequency of harmonic fields generated by the traction winding is low and it is, therefore, difficult to attenuate them. These low frequency harmonic fields generate losses in the SC coils and often force them to go normal. However, in the EMS system, the whole flux mostly remains confined inside the iron-core at all speeds and therefore does not have the inherent shielding problem of the EDS system. Because of the iron in the EMS system, stray field in the passenger compartments is also well below the acceptable levels whereas in the EDS systems this field is usually too high in the passenger compartment and it must be reduced down to acceptable levels by introduction of shielding materials at additional cost/weight penalty. The EMS can use conventional rebar in the guideway but the EDS system must use non-magnetic non-conductive rebar.

The Grumman baseline magnet configuration was selected on the basis of extensive 2-D and 3-D magnetic analyses to meet the levitation and propulsion requirements. The selected magnetic system design employs 48 magnets, 24 on each side of a 100 passenger vehicle. The polepitch is 750 mm and the gap between the magnet poles and the rail is 40 mm. The NbTi SC coil has a modest ampere-turns

---

[*] This work was supported by the U. S. Army Corps of Engineers under a contract DTFR53-92-C-000 04

(50,000 AT) requirement, experiences a peak field of ~0.35 T and operates at 4.5 K. High temperature SC leads are specified for minimizing the helium boiloff. Because of the iron core the SC winding experiences little magnetic loads. The magnet is cooled with pool boiling liquid helium which is contained within the helium vessel of the coil. No helium refrigeration equipment is carried on-board the vehicle. Instead the boiled-off helium gas is compressed into a nitrogen cooled storage tank. Sufficient quantity of liquid helium is carried on-board for an uninterrupted 24 hour operation. At the end of a day, the gaseous helium is discharged at a central location for reliquefication and the liquid helium supply in the magnets is replenished.

INTRODUCTION

The important aspect of the Grumman Electromagnetic Suspension (EMS) system design [1] is the ability to levitate the vehicle, with a wide airgap 40 mm (1.6 inch), using iron cored SC magnets located along both sides of the vehicle's length. The magnetic field in the gap is also utilized to propel the vehicle at speeds up to 134 m/s using 3-phase propulsion coils embedded in the iron rail slots. The ability to accomplish this levitation and propulsion under a wide range of maneuvers, guideway irregularities and aero disturbances without saturating the iron is a complex task requiring extensive magnetic and control system analysis.

Figure 1 shows the baseline EMS magnet system consisting of an iron-cored magnet and a guideway iron rail. The laminated, iron-cored magnets and iron rails are oriented in an inverted "V" configuration (see [1] for details) with the attractive force between the magnets and rails acting through the vehicle's center of gravity (cg).

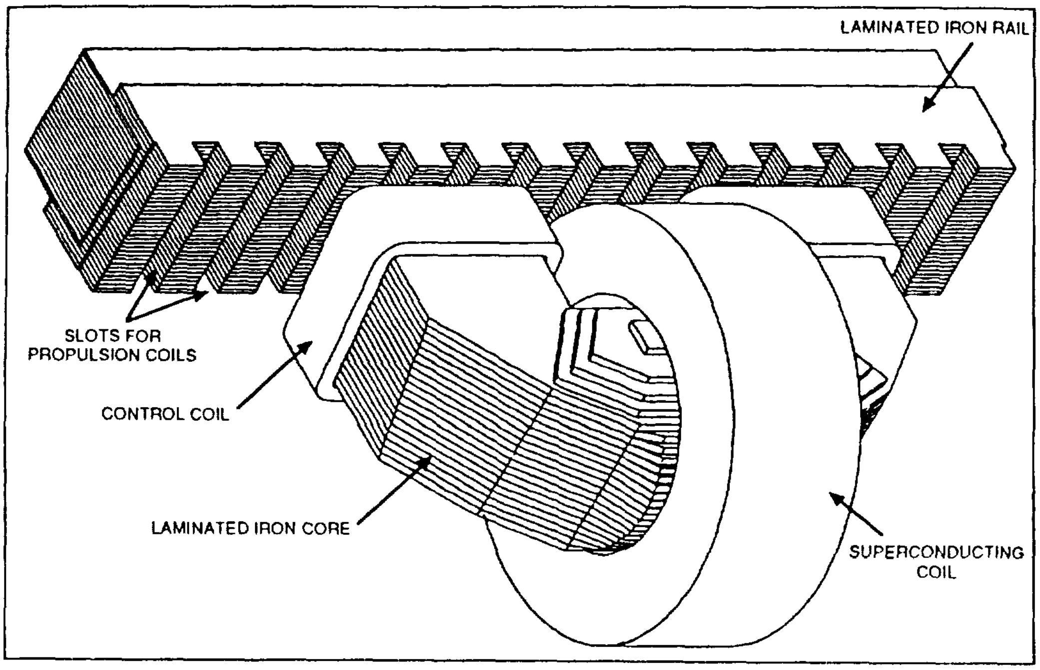

Figure 1. EMS Levitation and Propulsion Systems

The vertical control forces are generated by sensing the average gap clearance on the left and right side of the vehicle and adjusting the current in the control coils mounted on the magnet poles to maintain a constant 40 mm (1.6") gap. Lateral control is achieved by differential measurement of the gap clearance between the left and right sides of the vehicle. The corresponding magnet control currents are differentially driven for lateral control. In this manner, control of the vehicle relative to the rail is achieved in the vertical, lateral, pitch, and yaw directions. For roll control, the C-magnet assemblies are alternately off-set with respect to the rail width by 20 mm. With this arrangement, if the vehicle deviates from the nominal operating position, the lateral forces generated between the poles and the rails are such that they drive the system back to the equilibrium state. This process is further helped by sensing the vehicle's roll position relative to the rail and differentially driving the offset control coils to correct for roll errors. The iron rail on the guideway is laminated and carries 3-phase propulsion winding powered by a variable frequency ac source synchronized to the vehicle speed. Vehicle housekeeping power is inductively induced into coils mounted on the pole faces of each magnet.

REQUIREMENTS

The total weight of a 100 passenger fully-loaded vehicle is ~ 60,000 Kg. The force generated by the magnet system must be 90% larger to provide lateral guidance in the inverted "V" configuration. The total baseline levitation and guidance force to be provided by the magnet system is 115,000 Kg. A load variation of +/- 45,000 Kg is required about the baseline value for rapid gap control. These and other baseline requirements are summarized in Table I. The vehicle has 18 m length available for accommodating the SC magnets and an airgap of 40 mm must be maintained between the levitation magnet pole faces and the rail. By reacting with 3-phase AC windings housed in the rails, these levitation magnets also generate a propulsion force of 6,000 Kg for nominal operation and 10,000 Kg for extended operation. The extended operation includes the requirements for accelerating on uphill grades, against head-wind, etc.

Table I. Maglev Vehicle Requirements

PARAMETER	UNIT	VALUE
Baseline levitation per vehicle	Kg	115,000
Load variation	Kg	45,000
Vehicle magnetic length	m	18
Airgap between poles and rail	mm	40
Propulsion force - nominal	Kg	6,000
- extended	Kg	10,000
Maximum vehicle speed	m/s	134

The levitation magnets must also generate sufficient lateral force to counter roll moments. Furthermore, the SC magnets must be designed for reliable operation and for easy maintenance.

BASELINE DESCRIPTION

Pole Configuration

The baseline C-magnet and rail configuration is shown in Fig. 2. The key parameters of the baseline magnet system are summarized in Table II. Each C-magnet assembly consists of a C-shaped iron core, a SC magnet located around the back leg of the iron core, and normal control coils around each pole of the iron core.

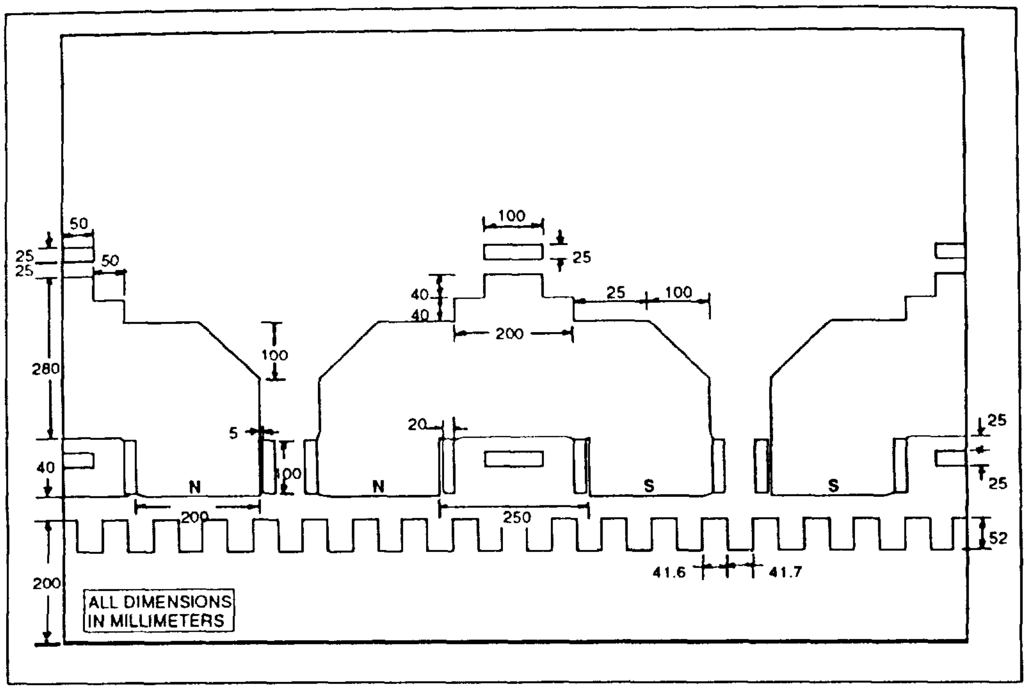

Figure 2. Baseline Pole and Rail Geometry

Table II. Baseline Levitation Magnet and Rail Parameters

PARAMETER	UNIT	VALUE
Lift capability per pole	Kg	2,400
Variation in lift capability	Kg	940
Pole pitch	mm	750
Number of poles		48
Airgap length	mm	40
Peak of sinusoidal field component in airgap	T	0.9
Operating frequency at rated speed	Hz	89
Nominal lift-to-weight ratio		6.4
Rail width	mm	200
Rail thickness	mm	200
Number of slots/pole in the rail		9

As shown in Fig. 2, the C-magnet assemblies are arranged such that the polarity of the poles of adjacent C-magnets is identical. Thus a pole (N or S) is formed by two legs of adjacent C-magnet assemblies. This arrangement of poles is the same as that accomplished with a continuous row of magnet poles on a single magnet core assembly. The baseline pole pitch is 750 mm.

Each pole face also has five slots (as shown in Fig. 3) for accommodating coils for inductive power generation on-board the vehicle for operating equipment and housekeeping services. These coils generate power at zero and low speeds by high frequency transformer action, and from airgap flux pulsations at high speeds. This power generation concept is described in [2]. The poles are skewed (Fig. 3) to minimize the effect of traction winding space harmonics on the traction force.

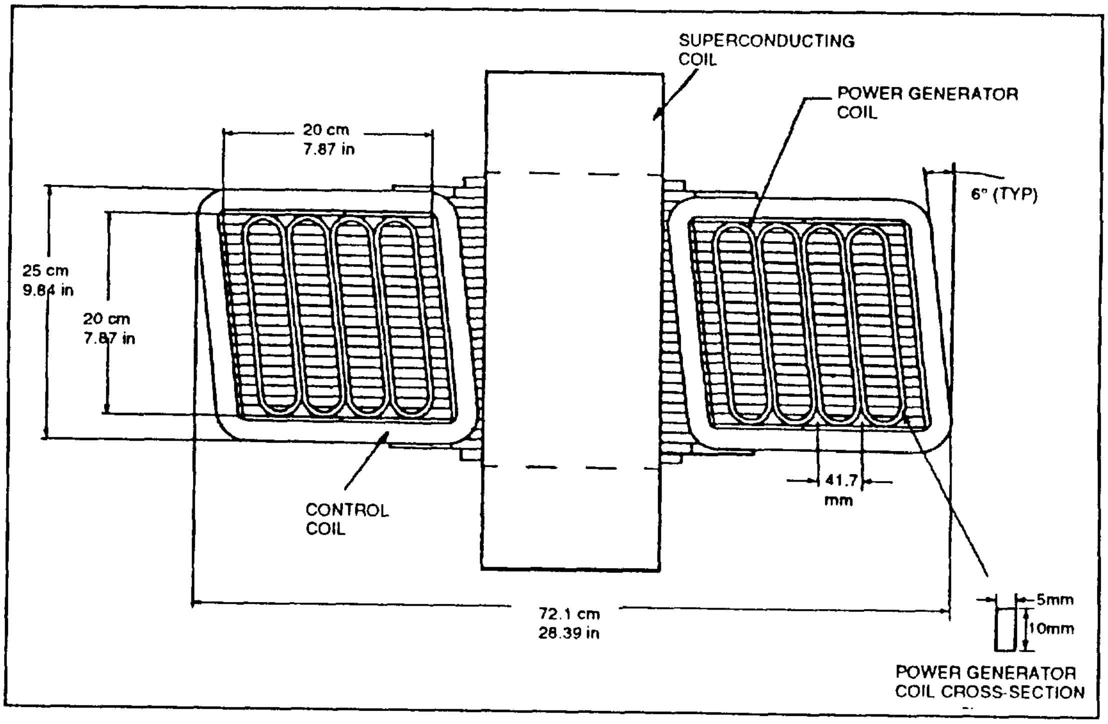

Figure 3. Skewed Magnet Poles with Power Generator Coils

Principle of Magnet System Operation

The SC magnet on a C-core operates in a quasi-steady state. During operation, any change in the size of the airgap tends to change the flux in the gap and in the core. When this happens, the current in the control coils is modulated to restore the flux in the airgap to its original value. This is accomplished with the help of a gap control system shown in Fig. 4 and is discussed below.

For reasons of SC coil stability and heat loads, the SC coil is supplied from a constant current source that has built-in capability to prevent current changes occurring faster than ~ 1 Hz. On the other hand, the airgap is expected to change at frequencies up to 10 Hz. The normal control coils develop self currents in response to these oscillations of gap length with an intent to restore the gap to its nominal value. If a steady change in the gap is noticed (due to increased or decreased load), then the current in the SC coils is allowed to change so as to drive long-term currents in the normal coils to zero. It is possible to achieve a certain degree of damping with the shorted coils. But in a practical system, it is essential to dynamically control these coils to respond to gap variations resulting from passenger load changes, maneuvering around curves or during grade changes of a given route. For this purpose, the airgap is constantly monitored and current of appropriate polarity is supplied to each normal coil for maintaining the nominal gap. This concept is described in more detail in [3].

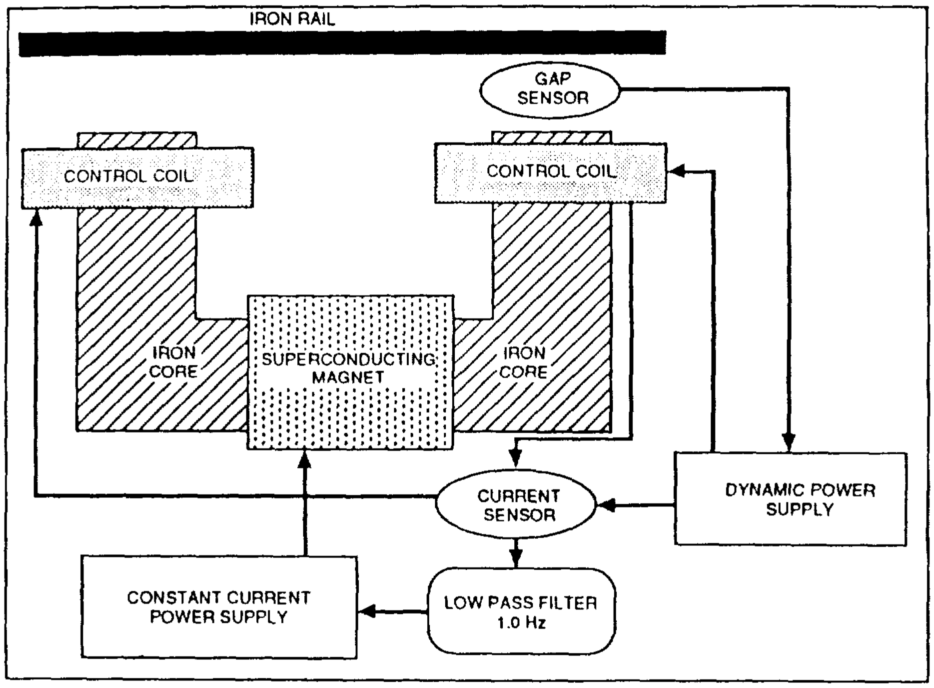

Figure 4. Magnet Control System

Effect of Normal Control Coils on the Levitation Force

The normal control coils are provided to compensate for fast changes in the required levitation capability. A set of calculations were performed to estimate the effect of control coil ampere-turns on the levitation force as a function of airgap length. Because of very high field levels in the iron core, it was decided to perform these calculations with 3-D codes (both TOSCA and ANSYS were used). Fig. 5 shows the combined lift and guidance force as a function of control coil current for constant gap lengths. The same data is presented in Fig. 6 but as a function of gap length for constant values of control coil currents. In both figures, the magnet is nearly a linear function of gap length and control coil current around the nominal operating point of a 40 mm gap and zero control coil current. When the core saturation increases, the relationship becomes non-linear. However, the important factor is to generate a sufficient amount of levitating force variation to maintain controllability of the vehicle and this objective has been achieved [4].

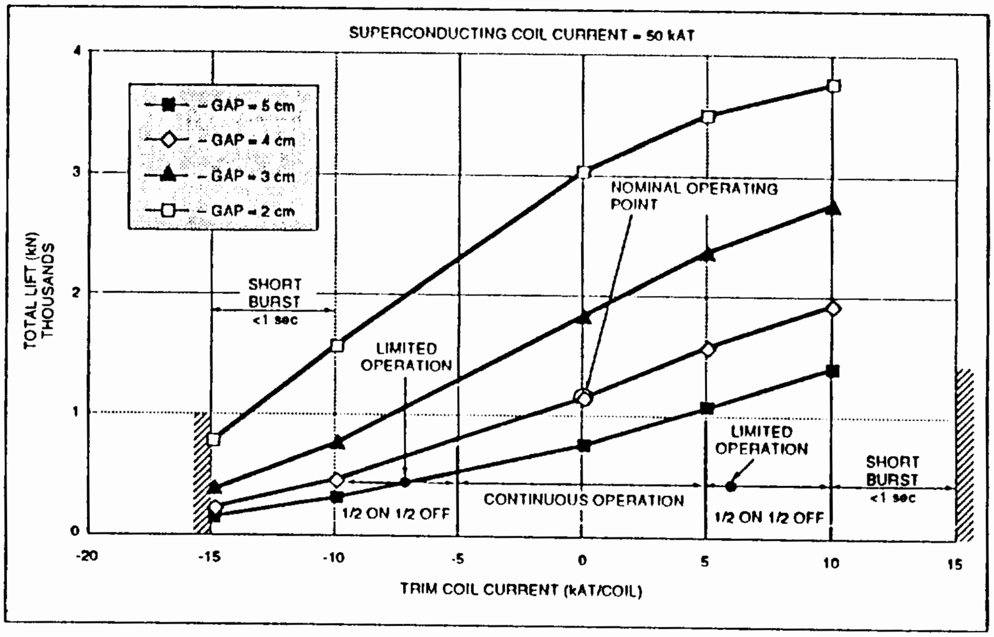

Figure 5. Levitation vs Control Coil Current for Constant Airgap Lengths

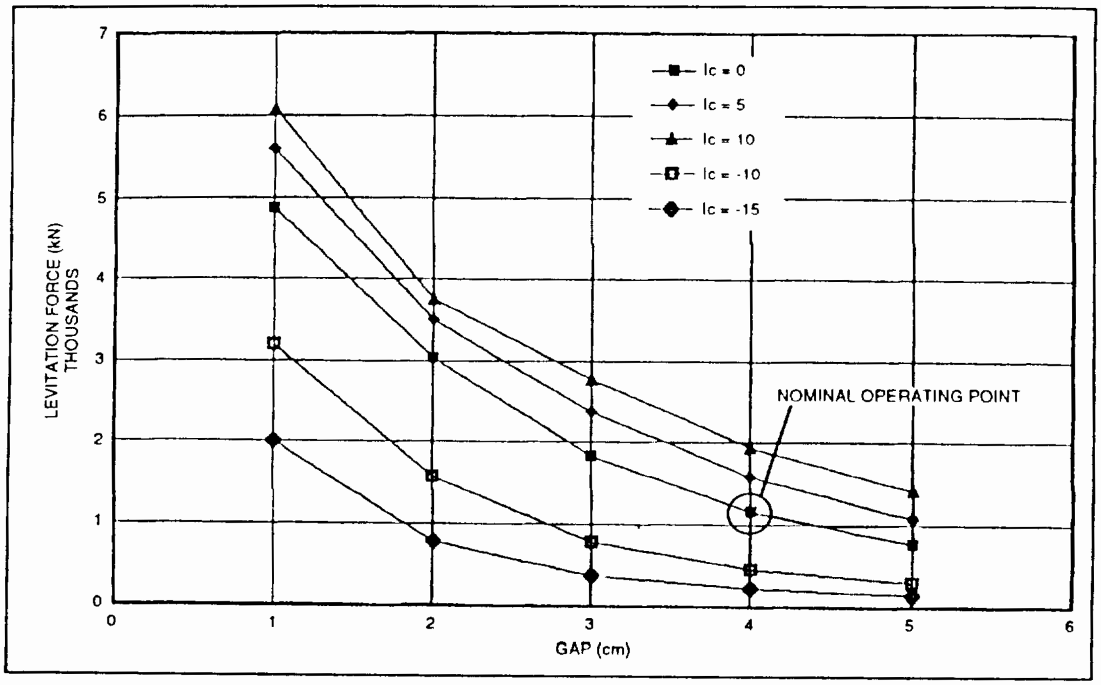

Figure 6. Levitation vs Airgap Length for Constant Control Coil Current

Roll Control

The EMS maglev concept proposed here is inherently stable against roll rotation. This is achieved by off-setting C-magnet poles with respect to the rail. Two C-magnet assemblies are carried as a module. Alternate magnet modules are shifted laterally with respect to the rail by about 20 mm. As a result of this shift, a lateral force is generated between the poles and the rail. The total of forces on all poles sums to zero during normal operation. During a transient condition, if all poles move to one side with respect to the rail, the force decreases on poles that are getting aligned with the rail and the force increases for poles that are getting more misaligned. The net force always tends to return the system to the equilibrium state.

An estimate of the lateral restoring force was made with a 2-D finite element analysis. The lateral force as a function of misalignment is shown in Fig. 7. The permanent misalignment between the poles and rails is initially fixed at 20 mm. The restoring force for this misalignment is 890 N/pole; this is about 4% of the nominal levitation force and is considered adequate for most operating scenarios.

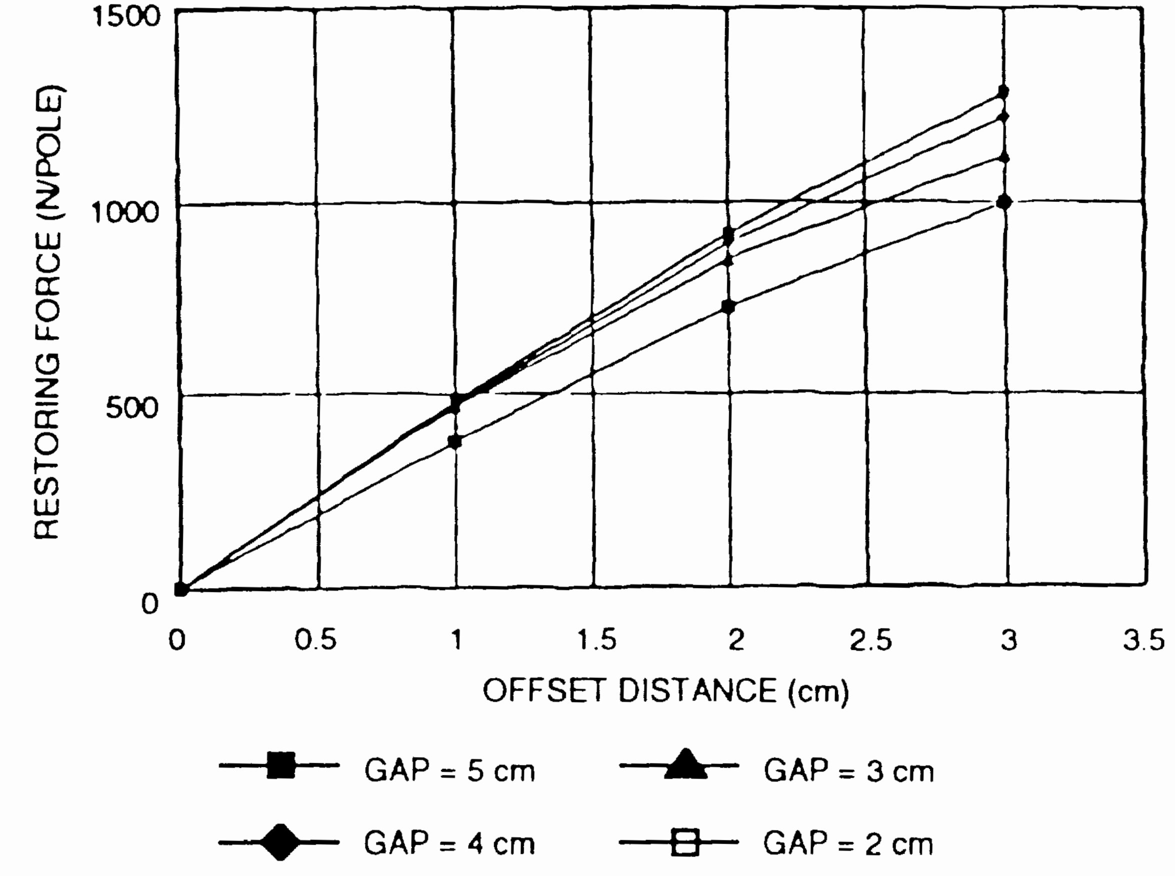

Figure 7: Lateral Restoring Force

Stray Magnetic Field Level

3-D magnetic field calculations were performed to estimate stray field in the passenger compartment and the surrounding areas. The flux density levels below the seat are less than 1 G, which is very close to the ambient earth's field (0.5 G). On the platform, magnetic field levels do not exceed 5 G, which is considered acceptable in hospitals using magnetic resonant imaging (MRI) equipment. These results were obtained without any shielding. With a modest amount of shielding, these field levels could be further reduced should future studies indicate a need for lower values.

ESTABLISHING POLEPITCH

The sizing of both the depth of the rail guideway magnetic core and the core depth of the vehicle magnets is directly proportional to the polepitch. Thus the polepitch is the key factor in establishing overall system weight and steel materials cost.

The C-magnet and rail configuration of Fig. 2 was utilized for performing a parametric study to select an optimum polepitch that minimizes the overall cost of a Maglev system consisting of a double 300 mile track with 100 cars operating at any given time. The study was performed to satisfy requirements of Table I. The results of the study are summarized in Fig.8. As can be seen , the cost of the system continually increases with polepitch because a larger polepitch requires a deeper (thicker) rail to carry the magnetic field. A certain level of airgap field is required for the levitation capability, but it is not proportional to the polepitch because increasing the polepitch also improves the levitation efficiency of the magnet (large poleface to airgap length ratio). The lowest polepitch of 750 mm was selected on the basis of a volumetric constraint to accommodate the SC coil, its cryostat and the two normal control coils.

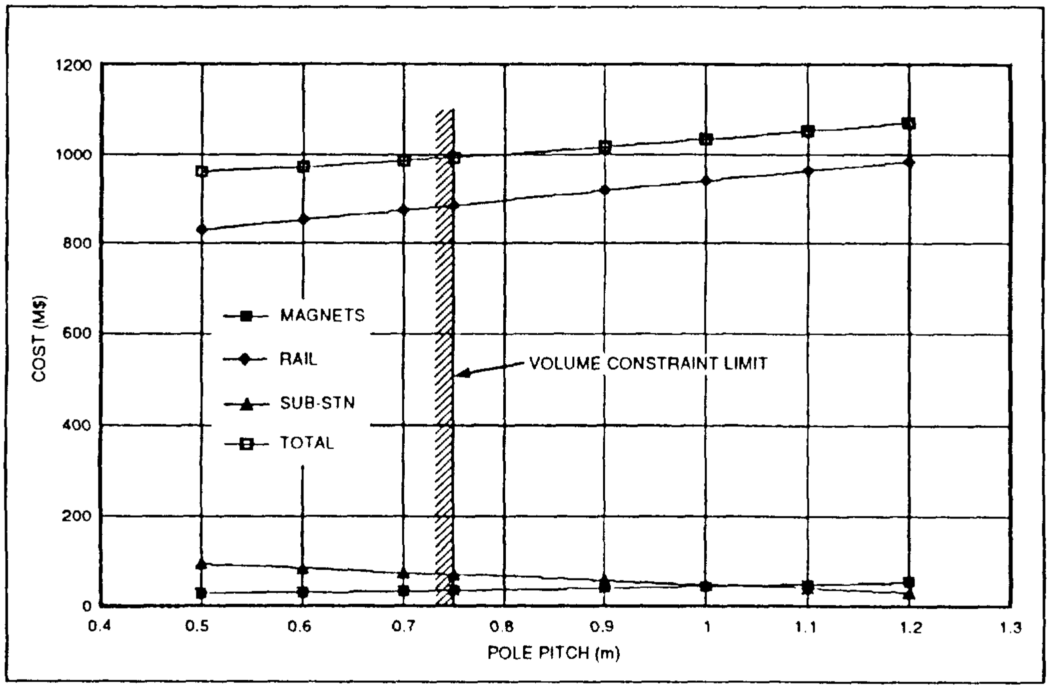

Figure 8. Maglev Levitation System Cost vs Polepitch

ESTABLISHING NUMBER OF MAGNETS REQUIRED

The 3-phase traction winding in the rail requires that the field produced by the excitation poles on the car (iron cored DC magnets) be sinusoidal in shape and its harmonic components be as small as possible for minimizing their deleterious effect on the traction force and eddy-current losses. The suspension magnets provide the key functions of levitation and propulsion simultaneously in the EMS system. Because of this constraint, a minimum number of poles are required for a given airgap magnetic field strength to accomplish the tasks of levitating and propelling the vehicle.

The analysis to determine the minimum number of poles follows. The levitation force generated by a sinusoidal field is given as:

$$F_l = 0.5\, w\, \tau\, \{B_m^2/(2\mu_o)\}\, N_p \qquad (1)$$

where Fl = levitation force (N)
B_m = peak of the sinusoidal field (T)
w = width of the rail (m)
τ = polepitch (m)
μ_o = permeability of air = 4 p 10^{-7}
N_p = number of pole on a vehicle

Similarly the total traction force (N) per pole is:

$$F_t = 1.5\, B_m\, I_m\, q\, w\, \eta K_d\, N_p \qquad (2)$$

where Im = Peak of the sinusoidal current in traction winding (A)
q = slots per pole per phase in the rail
η = Efficiency of traction motor ˜ 99%
K_d = Distribution for the traction winding

After eliminating B_m between (1) and (2), the equation for the number of poles is:

$$N_p = \{F_t^2/F_l\}\, \{\tau/(I_m^2\, q^2\, 9\, \mu_o\, w)\}/(\eta^2\, K_d^2) \qquad (3)$$

The baseline values for various variables are:

- F_t = 60 kN
- τ = 0.75 m
- q = 3
- η = 0.99
- F_l = 1,150 kN
- I_m = 1,900 A
- w = 0.2 m
- K_d = 0.96

With these values, the number of poles determined from Eq. (3) is 36. The baseline is fixed with 48 poles to provide redundancy.

MAGNET DESIGN

Magnetic Analysis

Initially a majority of calculations were performed with 2-D code (EMP, a commercial version of POISSON code) assuming a M43 iron core material. Fig. 9 shows field distribution calculated with the 2-D code in the airgap, pole and rail iron.

Table III. Comparison of Field Values Calculated with 2-D and 3-D Codes for the Baseline

LOCATION (SEE FIG. 9)	**2-D FIELD (T) M43 IRON**	**3-D FIELD (T) M43 IRON**	**3-D FIELD (T) Permendur**
A	1.21	2.45	2.47
B	0.89	1.73	1.2
C	0.8	0.87	0.88
D	1.33	1.52	1.45

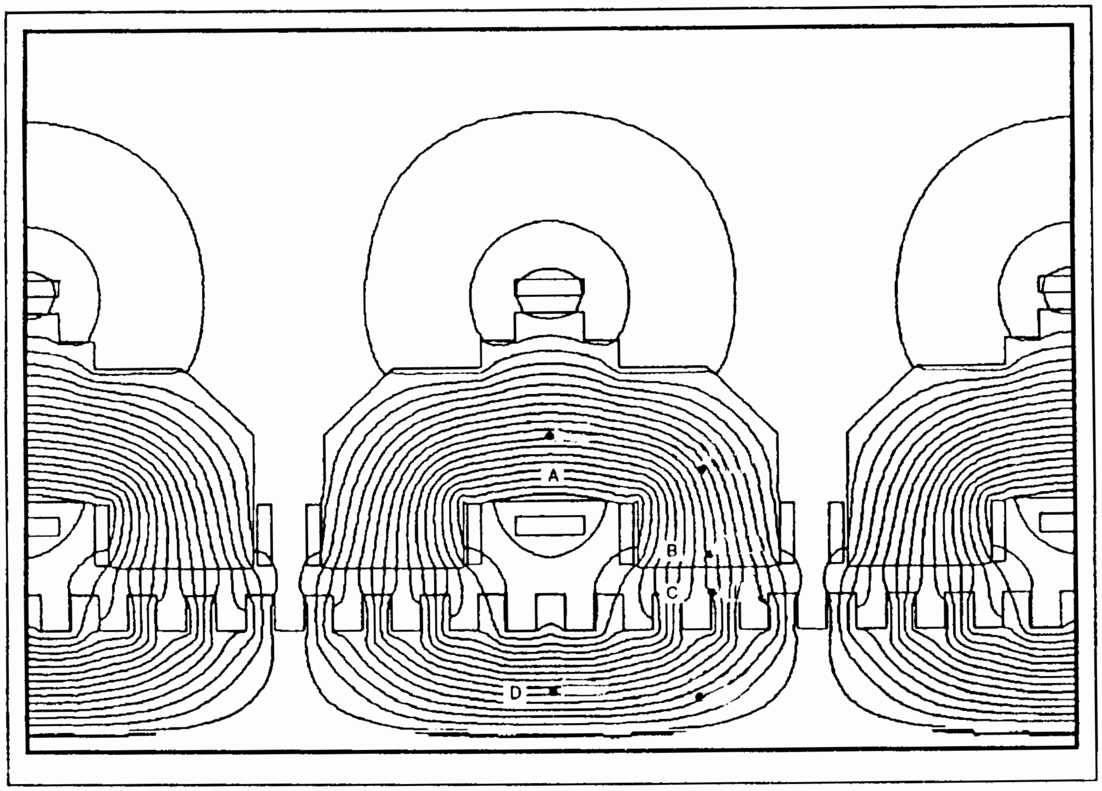

Figure 9: Baseline Magnetic Field Calculations with 2-D Code

Fig. 10 shows field distribution calculated with a 3-D code (TOSCA). The field distribution calculated by the two codes for the airgap is similar, but the 3-D calculation summarized in Table III shows a much higher degree of saturation of the pole-iron (in the vicinity of the SC coil). To reduce this saturation to a reasonable value, a permendur iron (2% vanadium, 49% iron, and 49% cobalt) was specified in place of the M43 material. Table III also compares the resulting field values for the M43 iron and the baseline permendur pole iron. The SC coil provides 54 kA-turns. Locations of field comparison are marked in Fig. 9. The penalty for selecting a permendur iron for the poles instead of M43 is approximately 7% of the vehicle cost.

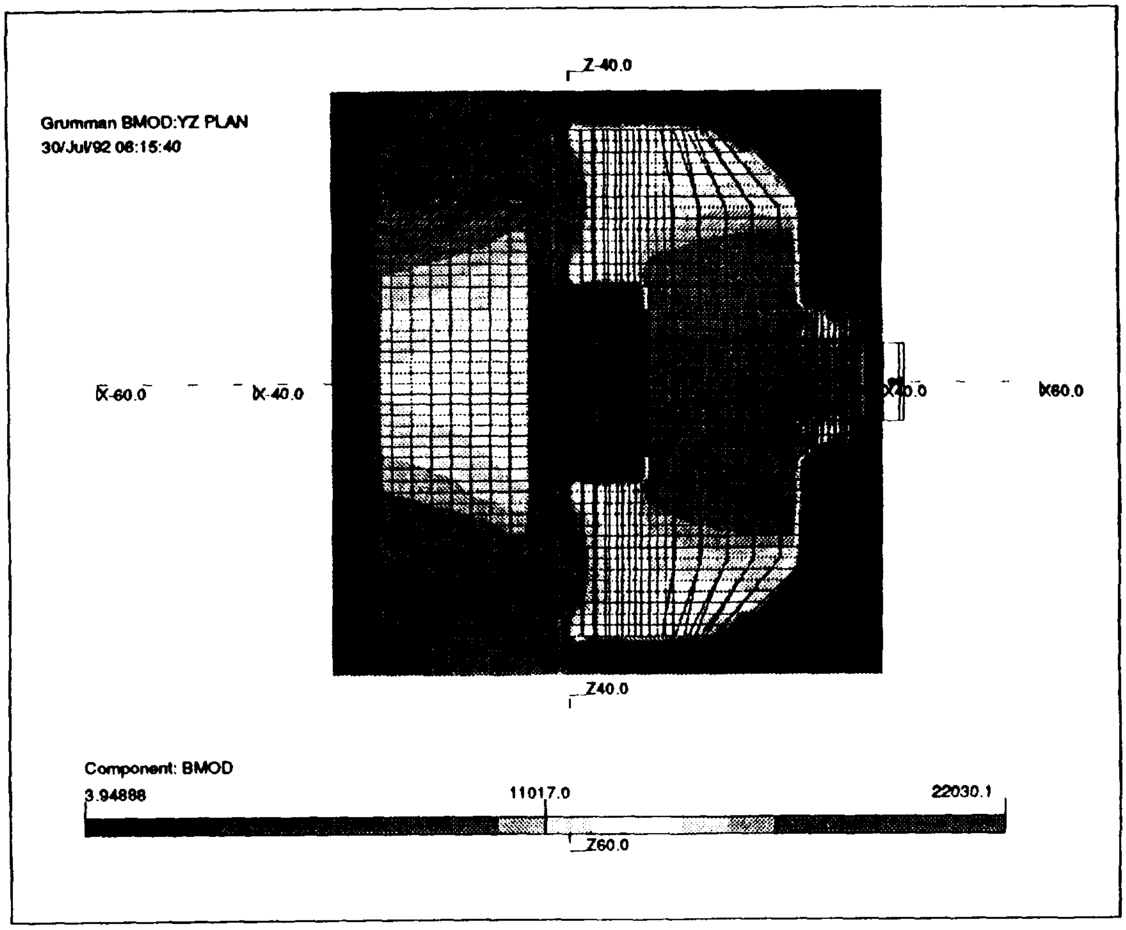

Figure 10: Baseline Magnetic Field Calculations with 3-D Code (Permendur Iron)

Sizing of SC Coil and Cryoplant

A cylindrical SC coil and cryostat were selected for each C-magnet assembly since they are easier to fabricate and are lighter in weight than non-cylindrical shapes. For this reason, the iron core cross-section under the magnet is made circular. The iron is built from 0.050 inch thick laminations (Permendur.)

The SC coil carries 54 kA-turns to produce the required field to simultaneously meet requirements of levitation and propulsion. The SC coil is designed by using a 0.65 mm diameter NbTi wire that has been developed by Brookhaven National Laboratory for their Relativistic Heavy Ion Collider (RHIC) dipole magnets. The key parameters for the SC coil are summarized in Table IV.

Table IV. SC Coil Parameters

Parameter	**Unit**	**Value**
Ampere-turn rating of SC coil	kA-turn	54,000
Peak field at the SC coil	T	0.5
Operating current	A	53
Operating temperature	K	4.5
Number of turns		1,020
NbTi wire diameter - bare	mm	0.6477
Copper-to-superconductor ratio		2.2
Ratio of Operating to critical current		0.09
Temperature margin to current sharing	K	3.69

The SC coil has 1,020 turns; each turn carries 53 A to produce required 54 kA-turns. These turns are accommodated in a coil pack of 4 layers with 255 turns in each layer.The coil pack is epoxy impregnated to produce a monolith structure. No separate quench protection system is required because the energy stored in the magnet is very small. In the event of a quench, the magnet is disconnected from the supply and is shorted at its terminals.

The total heat load for the magnets on each car is 8 W. The weight and the cost of a cryogenic refrigeration plant would be 2,540 Kg and $110,000 respectively. It also will be necessary to supply ~16 kW of power to run the refrigerator plant. To mitigate the weight and operating power penalty a decision was made to employ a cryogenic storage system. The liquid helium cryogenic storage system consists of a small compressor operating at 350 psi that takes the gaseous helium boiloff and compresses it into a storage tank held at liquid nitrogen temperature. Sufficient helium inventory is carried in the magnet for a 24-hour continuous operation. The gaseous helium storage system is sized to accommodate helium boiloff over a 24-hour period. At the end of the 24-hour period, the gaseous helium is discharged at a central location and liquid helium is replenished in the magnets. Two cryogenic storage systems are provided for each 50 passenger module. The weight of each cryogenic system is 580 Kg which includes 180 Kg for a compressor and 400 Kg for the gaseous helium storage tank.

Potential of Using High Temperature Superconductors

The iron cored SC magnets of the Grumman concept are in the best position to take advantage of the new High Temperature Superconductor (HTS) technology. The peak field in the iron is greater than 2 T, but in the SC winding region it is less than 0.35 T. The superconductor is also required to supply a modest 54 kA-turns to generate the required field for vehicle levitation and propulsion.

Because of very small fields and forces experienced by the SC coil and recognizing rapidly advancing state-of-the-art of the HTS technology [5], Grumman considers that this Maglev concept is in a best position (relative to all other SC magnet Maglev concepts) to take advantage of the HTS technology. The following are the attractive features of the HTS magnet:

- Operation at liquid nitrogen temperature (77 K)
- No need for liquid helium compressor or storage tanks
- Simpler and lighter cryostat
- Lower weight and capital cost
- Lower manufacturing cost
- Lower operating and maintenance cost

The current state-of-the-art of HTS is sufficiently developed so that an HTS coil could be built for the Grumman Maglev. The HTS conductors [6] have acceptable current densities and are made in sufficiently long lengths to suit EMS magnet needs.

CONCLUSIONS

The Grumman developed EMS Maglev system has the following key characteristics:

- A large operating airgap - 40 mm
- Levitation at all speeds
- Both high speed and low speed applications
- No deleterious effects on SC coils at low vehicle speeds
- Low magnetic field at the SC coil - <0.35 T
- No need to use non-magnetic/non-metallic rebar in the guideway structure
- Low magnetic field in passenger cabin ~ 1 G
- Low forces on the SC coil
- Employs state-of-the-art NbTi wire
- No need for an active magnet quench protection system
- Lower weight than a magnet system with copper coils

The EMS Maglev described in this paper does not require development of any new technologies. The system could be built with the existing SC magnet technology. The future work is planned to improve the design to minimize high magnetic fields in the iron core and to consider the possibility of replacing the helium cooled NbTi SC coils with nitrogen cooled High Temperature Superconductors.

REFERENCES

[1] M. Proise, et al. "System Concept Definition of the Grumman Superconducting Electromagnetic Suspension (EMS) Maglev Design", presented at the Maglev '93 Conference, Argonne National Laboratory, May 19-21, 1993.

[2] S. Kalsi, "On-vehicle Power Generation at all Speeds for Electromagnetic Maglev Concept", presented at the Maglev '93 Conference, Argonne National Laboratory, May 19-21, 1993.

[3] R. Hurbermann,"Self Nulling Hybrid Maglev Suspension System", presented at the Maglev '93 Conference, Argonne National Laboratory, May 19-21, 1993.

[4] R. Gran and M. Proise,"Five Degree of Freedom Analysis of the Grumman SC Maglev Vehicle Control/Guideway Interaction", presented at the Maglev '93 Conference, Argonne National Laboratory, May 19-21, 1993.

[5] P. Halder and L. Motowildo, "Recent Development in the Processing of High Jc Silver Clad Mono- and Multi-Filament (Bi, Pb)2Sr2Ca2Cu3O10 Wires and Tapes,"Journal of Metals, October 1992.

[6] P. Haldar, J. Hoehn, Jr., U. Balachandran, and L. Motowildo, "Processing and Transport Properties of High-Jc Silver-Clad Bi-2223 Tapes and Coils", Proceedings of the Symposium on High Temperature Superconductors, 1993 TSM Annual Meeting, Denver, CO, February 21-25, 1993.