APPENDIX A: RIDE COMFORT GUIDELINES

This appendix gives the new ride comfort guidelines sent to the contractors after the SCD-RFP was issued.

A1. Ride vibration regime 1.0–25 Hz

Pepler equation

- 4-Minute moving window for root mean square calculation.
- Measurements at center of percussion.
- Pepler equation is the "composite" method described in *Development of Techniques and Data for Evaluating Ride Quality* (Pepler et al. 1978).
- Calculated only for reference

ISO (International Standard 2631/1, 1985, Fig. A1).

- 50-Second moving window for RMS in 1/3 octave band analysis.
- Measurements at worst case seat in local coordinates.
- Design goal—1-hour reduced comfort.
- Minimum requirement—15-minutes reduced comfort.

A2. Motion sickness regime 0.1–1.0 Hz

- ISO extended (Fig. A2).
- 4-Minute moving window for RMS in 1/3 octave band analysis.
- Measurements at worst case seat in local coordinates.
- Design goal—1-hour reduced comfort.
- Minimum requirement—15 minutes reduced comfort.

A3. Curving performance

Table A1. Average values for event (i.e., spiral or curve).

	Design	*Min. Req.*	*Seat/Belt*
a. Lateral curves			
Bank angle	24°	30°	45°
Roll rate	5°/s		10°/s
Lateral	0.1 g's	0.16	0.2
Roll accel.	$15°/s^2$		
b. Vertical curves (g)			
Vertical (up)	0.05	0.1	0.1
Vertical (down)	0.2	0.3	0.4
c. Acceleration and braking (g)			
Normal	0.16	0.2	0.6
d. Vector combinations (g)			
Lat./long.	0.2	0.3	0.6
Lat./vert.	0.2	0.3	0.4
Total	0.24	0.36	0.6

Table A2. Jerk (g/s filtered at 0.3 Hz) or jolt (peak to peak g's in 1 second).

	Design	*Min. Req.*	*Seat/Belt*
Lateral	0.07	0.25	0.25
Vertical	0.1	0.3	0.3
Longitudinal	0.07	0.25	0.25

A4. Other factors

- Temperature: 18–23°C
- Noise: 70–75 dBA

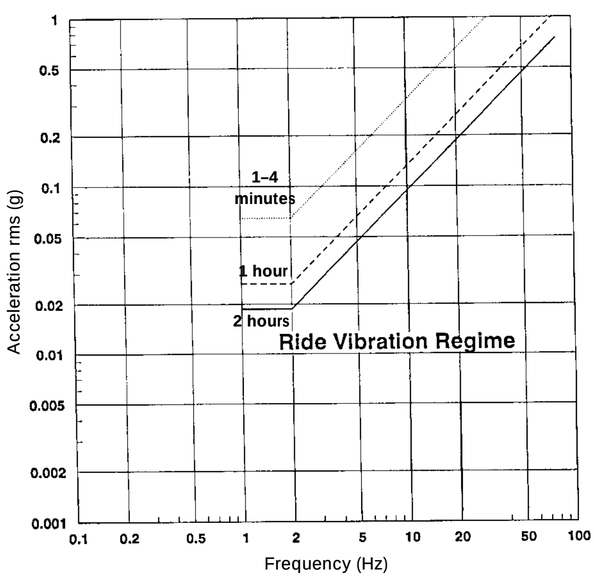

Figure A1. ISO vibration exposure limits for lateral acceleration.

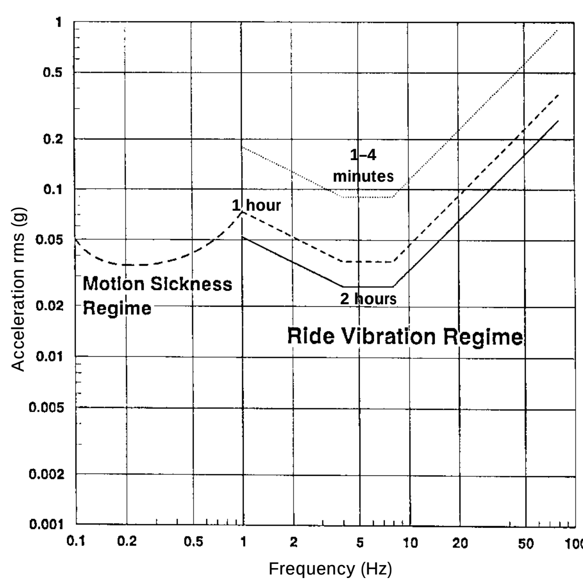

Figure A2. ISO vibration exposure limits for vertical acceleration.

BLANK

APPENDIX B: WIND SPECIFICATIONS FOR MAGLEV SYSTEM CONCEPT DEFINITIONS

To ensure that maglev systems possess superior adverse weather performance to alternative modes, SCD contractors shall treat wind thresholds I and II (defined below) as minimum requirements.

B.1 Threshold I—operational wind threshold

During wind conditions that are less severe than this threshold, a maglev system will operate at 100% capability. That is, the system will maintain its maximum potential throughput and acceptable levels of safety and ride comfort during wind conditions below threshold I. Threshold I wind conditions are as follows:

- A 1-hour average wind speed of 13.4 m / s (30 mph) any direction.
- A peak gust of 21 m / s (47 mph) any direction.

Gust velocity spectrum is defined below.

These conditions occur, on average, six times per year at Boston, Massachusetts, and 13.4 m / s represents roughly twice the crosswind speed that disrupts landings of light commercial aircraft. Also, the 1-hour average and 1-second gust specifications are compatible with the referenced spectrum.

B.2 Threshold II—structural wind threshold

For wind conditions that are less severe than this threshold, a maglev system will experience no structural failure. That is, the support structure (guideway, piers, footings, and all attachments including motor elements), any vehicles on it, and all power, communications, command, and control equipment will be fully operational following a wind condition below threshold II.

Contractors shall use the methodology defined below for determining wind loads at threshold II (ASCE 1990):

$$F = q_z G_h C_f A_f$$

where
- F = wind load (N)
- q_z = velocity pressure ($0.613\ K_z\ [I\ V]^2$, N / m^2)
- K_z = exposure coefficient
- I = importance factor
- V = basic wind speed (m / s)
- G_h = gust response factor
- C_f = force coefficient
- A_f = projected area normal to wind (m^2).

Default values are as follows:

$$K_z = 1.0$$
$$I = 1.10$$
$$V = 38 \text{ m / s (85 mph)}$$
$$G_h = 1.25$$
$$C_f = 2.0.$$

These default values represent wind conditions over flat, open terrain at a height of 10 m. A basic wind speed of 38 m / s or less represents a 50-year mean recurrence speed over about 90% of the continental U.S. An importance factor of 1.10 is suitable for regions within 160 km of a hurricane coastline (e.g., Northeast corridor).

Contractors shall include appropriate analyses to demonstrate that their concepts meet wind thresholds I and II. If they deviate from the values or methodology described above, they shall include appropriate technical justification.

In addition, contractors shall include supporting analyses and documentation that establish wind conditions representing thresholds III and IV for their concepts (as defined below).

B.3 Threshold III—vehicle safety wind threshold

During wind conditions that are less severe than this threshold, maglev vehicles may be present on the guideway. That is, vehicles may safely operate at reduced speed or may be safely stationary during wind conditions below threshold III. This threshold will be between thresholds I and II. Contractors must consider safety issues such as vehicle–guideway contact and vehicle derailment when determining this threshold.

B.4 Threshold IV—ride comfort wind threshold

During wind conditions that are less severe than this threshold, a maglev system will maintain acceptable levels of ride comfort but may reduce throughput to achieve it. This threshold will be between thresholds I and III.

Contractors shall specify thresholds III and IV as a 1-hour average wind speed and direction. To analyze dynamic effects, contractors shall use the gust velocity spectrum described in section B.5 or provide technical justification for using an alternative.

Contractors should examine relevant wind engineering literature to determine how wind may affect their concepts and to guide their analyses. The material presented in Simiu and Scanlan (1978) constitutes a general survey of this field.

B.5 Wind gust velocity spectrum

This is from Davenport (1961):

$$n S(n) / u_t^2 = 4.0\ x^2 / \left(1 + x^2\right)^{4/3}$$

where $S(n)$ = gust velocity spectrum ($[m/s]^2/Hz$)

n = gust frequency (Hz)
u_t = friction velocity (m/s)
x = $1200\ n / U_{10}$
U_{10} = 1-hour average wind speed at a 10-m height.

Also, the standard deviation u' is assumed to be

$$u' = 2.5\ u_t = U_{10} / 5.7.$$

APPENDIX C : ASSESSMENT OF THE POWER ELECTRONICS FOR THE LOCALLY COMMUTATED LINEAR SYNCHRONOUS MOTOR (LCLSM)*

C.1 LCLSM CONCEPT SUMMARY

The Foster-Miller, Inc., maglev concept takes an innovative approach to the linear synchronous motor (LSM) that is called the locally commutated linear synchronous motor (LCLSM). The LCLSM, a superconducting motor, has individually connected guideway coils that are connected in parallel to the power source. It requires variable frequency inverters at every LSM coil position on the guideway. The guideway coils that are opposite to each other are connected in parallel. Each pair of coils is then connected to and controlled by one H-bridge inverter. The concept requires LCLSMs to be located at approximately 1-m spacings along the guideway. This is in contrast to conventional blocklength LSMs (BLSM), which typically require the variable frequency inverters along the guideway to be located with separations of every 2 to 10 km.

The Foster-Miller concept makes use of a DC distribution system along the guideway. The voltage magnitude is 2 kV and has rectifier substations located at approximately 8-km intervals. Feeder cables connect the rectifier output to the LCLSMs. The feeder cables are sized to limit the voltage drop from the rectifier to the farthest LCLSM to 5% or less. The output of the rectifier substations is not intended to be regulated or controlled in normal operation.

The inverter power level required for each of the individual LCLSM inverters is significantly different from the inverter power level for the BLSM. The inverter power level for the LCLSM is in the range of 0.5 to 1.0 MVA per inverter, whereas the BLSM inverter power level is in the range of 10 to 20 MVA per inverter. The power ratings are further made different from each other by the on-time portion of each inverter's duty cycle (this is the time when the inverter is energized and supplying power to its LSM). The LCLSM's on-time per passing consist is on the order of 0.5 to 1.5 seconds; the corresponding BLSM's on-time is of the order of 4 to 10 seconds per passing consist.

The power electronics circuit technology selected by Foster-Miller for control of the LCLSM is a pulse-width-modulated voltage source inverter, operating at a switch modulation frequency of approximately 10 kHz. Foster-Miller chose this frequency to reduce the potentially adverse effects of harmonics contained in the LSM current, and to control the magnitude of the H-bridge current during low speed operation, since the 2-kV DC input voltage bus to the H-bridge is not a controlled parameter. The back EMF of the LSM is proportional to vehicle speed and, at low speed operation, the voltage difference between the back EMF and the DC input voltage is large. For low speed operation (this would also include acceleration), each conduction pulse time of the H-bridge at the 10-kHz rate must be made as small as possible to limit the peak current that the H-bridge devices must switch.

* Written by Frank L. Raposa, Consulting Engineer.

C.2 APPLICATION OF POWER ELECTRONICS DEVICES

C.2.1 Review of power electronics device technology

Power electronics devices can be grouped into two categories, depending upon the basic junction structure of the device: the thyristor and the transistor. Thyristors are generally high-voltage and high-current devices, with ratings that can achieve several thousand amperes at several thousand volts. The commercially available devices in the thyristor family include the SCR (silicon controlled rectifier), the GTO (the gate turn-off thyristor), and the MCT ([metal oxide semiconductor] MOS-controlled thyristor). The SCR has been in commercial use for more than 25 years and the GTO for about 10 years. The MCT is about to be introduced in limited quantities and ratings.

Transistors are generally medium voltage and current devices with current ratings that can achieve a few hundred amperes at voltage ratings of several hundred volts in the higher current ratings, and with voltage ratings of about 1000 to 1500 V in the lower current ratings. The commercially available devices in the transistor family include the BJT (bipolar transistor), the power MOSFET (metal oxide field effect transistor), and the IGBT (insulated gate bipolar transistor). The BJT has been available for more than 30 years and the power MOSFET for less than 10 years. The IGBT has become commercially available only in the last year or so.

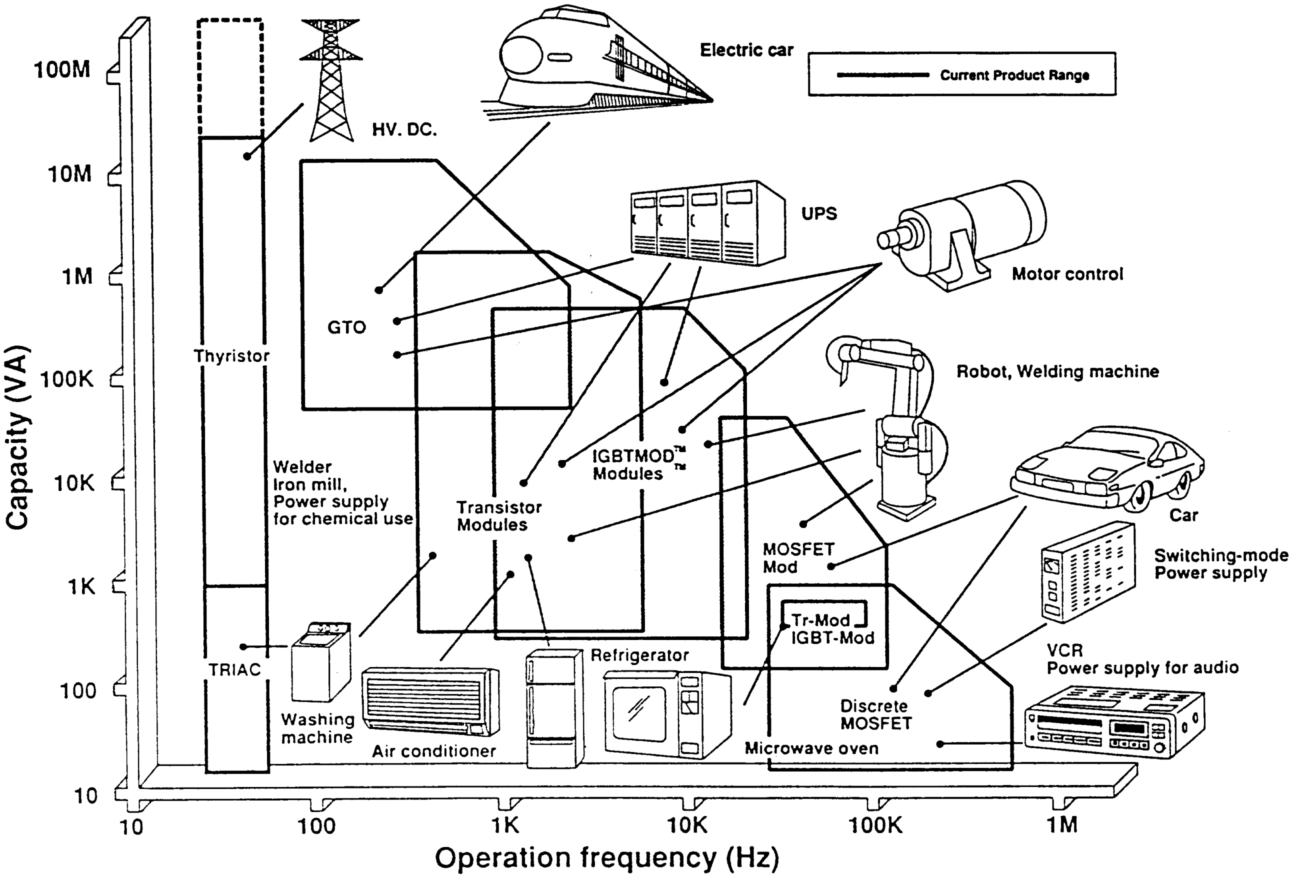

Figure C1. Typical applications for power electronics devices. (Line art courtesy of Powerex, Inc., and Mitsubishi Electric Company.)

The power module package was introduced some time ago to achieve higher ratings with transistor assemblies than are possible with discrete devices. With the power module package, several transistors at the semiconductor die level of fabrication are connected in parallel on a substrate to achieve current ratings of several hundred amperes. The mounting substrate, which is typically a copper-clad ceramic, has two major requirements. It must have good heat transfer capability and it must have high dielectric strength.

The assembly process for dual IGBT device modules uses each side of the substrate for mounting them. The current material used for the semiconductor die mounting substrate limits the voltage withstanding capability of the completed assembly to only about 3 kV DC. Consequently, this dielectric strength constraint limits the maximum voltage rating for a dual device power module to a maximum of about 3 kV. The high voltage IGBT dual device power modules that are currently available have rating capabilities that are slightly less than 3 kV for the two devices connected in series. Devices with these voltage ratings are available for only lower currents. Typical dual device ratings for higher current units are about 2.4 kV where they are connected in series. Research has been going on for some time to improve the substrate capability of power modules in both its thermal capacity and dielectric strength (Fishbein and Abramowitz 1992).

Figure C1, published by Powerex Inc. (Youngwood 1991) in their IGBT documentation, provides a comprehensive summary of power electronics device and module applications as a function of the device capacity in volt-amperes and the operating frequency that the devices switch in a power electronics circuit. One of the principal applications of GTOs is traction drives for rail systems; this includes equipment installed either in substations or vehicles. Other applications for GTOs include medium voltage (13.8-kV) motor drives used in utility systems. One of the major uses of both BJT and IGBT modules is for the control of motors that have the moderate voltage and current requirements that are compatible with the available ratings of these devices. The power MOSFET is principally used for nontraction applications in automobiles and to a lesser extent for high-frequency, low-power motor drives. The IGBT is likely to become a serious candidate for traction control in the emerging electric automobile market.

Power electronics devices were recently summarized at the IEEE Power Electronics in Transportation Workshop held in Deerborn, Michigan. Table C1 compares the BJT, MOSFET, IGBT, and MCT for several performance areas, including switching speed, current density, and voltage rating. The data provided for the MCT in this summary are conjectural, as this device is just coming out of its development cycle and is about to be introduced in only limited quantities and with limited ratings. A 600-V, 75-A device is about to be introduced by Harris Semiconductor, who are also evaluating devices with voltage ratings of 2 to 3 kV.

The recently completed BAA study on power conditioning for maglev concluded that GTOs are the best likely candidates for conventional LSM systems (Nerem et al. 1992). It also concluded that the IGBT is an attractive choice for the lower power level requirements of vehicle auxiliary power systems.

C.2.2 Application of power electronics for motor drive inverters (after Kassakian et al. 1991)

There are three major considerations in the choice and application of a solid-state device in power electronics circuits: the required current and voltage ratings of the device and its switching characteristics. The current imposed by the LSM on the device must be within its thermal ratings, since the internal junction temperature of the device must be kept within a specified limit. This junction temperature is usually set by design to be 125°C or less; this value is somewhat less than the maximum allowable semiconductor temperature of 150°C and leaves a slight design margin. Further, the thermal time constant of a power semiconductor is quite small and almost all design approaches operate on the assumption that the junction is always at steady-state temperature.

Table C1. Qualitative characteristics of solid-state switches (after Kajashekara 1992).

Field effect transistor (FET)	*Bipolar transistor*	*Insulated gate bipolar transistor (IGBT)*
O Optimally applied 50 to 200 V + Fast turn-on and turn-off O Reverse conducting (equal to forward current rating) + Wide safe operating area, no second breakdown; rugged O Positive temperature coefficient of resistance (parallel sharing) + Active device, conductivity modulated via gate + Little temperature effect on switching parameters □ High on-state resistance at high voltage ratings	O Optimally applied 500 to 1400 V + Medium turn-on and turn-off speed O Reverse blocking, but only at low voltage □ Safe operating area has second breakdown □ Negative temperature coefficient of resistance makes sharing difficult O Active device, conductivity modulated via base □ Temperature affects switching parameters □ High on-state voltage drop at high current □ Conduction requires base drive of 10% of forward current	+ Optimally applied 400 to 1200 V + Fast turn-on, medium turn-off speed O Reverse blocking, but to a low voltage + Wide safe operating area, no second breakdown + Positive temperature coefficient of resistance (parallel sharing) + Active device, conductivity modulated via base O 1-V threshold and then less than a linear voltage rise with current + Little temperature effect on switching parameters □ High on-state voltage drop at high voltage
Silicon controlled rectifier	*Gate turn-off thyristor (GTO)*	*MOS controlled thyristor (MCT)*
O Optimally applied 50 to 6500 V + Highest power device; lowest cost per watt switched □ Only turns off at zero current □ Negative temperature coefficient of resistance makes sharing difficult □ Requires recovery time for voltage hold-off after zero current + Reverse blocking to full forward voltage + Moderate turn-on time and dI/dt* + Low on-state voltage drop □ Device destruction if dI/dt rating is exceeded, but otherwise very rugged	+ Optimally applied 800 to 8000 V + Turns off with a gate counter-pulse—15% of forward current + Reverse blocking types available □ Negative temperature coefficient of resistance makes sharing difficult O Moderate turn-on time, but low dI/dt + Highest power self-commutated turn-off switch available + Moderate on-state voltage drop □ Device destruction if turn-off attempted above rating, if dI/dt rating is exceeded, if gate pulse is inadequate, or if retriggered too soon	+ Excellent promise for high voltage, low-loss turn-off switch □ Not commercially available □ Negative temperature coefficient of resistance makes sharing difficult O Loses turn-off capability above rating, but device will survive if turn-off is attempted

+ Advantage
O Typical characteristic
□ Disadvantage
* dI/dt = rate of current change

This is virtually a universally accepted assumption and is considered valid, unless a particular design requirement has the inverter operating at duty cycles that are significantly less than the microsecond-duration thermal time constant of the device. Heat removal techniques to assure safe junction temperature are a choice for the power electronics designer and there are many options that can be considered.

The voltage rating of the device is one of its most critical, as a solid-state power electronics device cannot withstand an over-voltage condition. An inadvertent device turn-on because of an over-voltage almost invariably leads to catastrophic failure either of the device itself or the inverter. Because it is very difficult to accurately specify all voltage conditions that may exist in a system (i.e., over-voltage surges resulting from transients coupling into the power system), it is common practice in designing power electronics circuits to significantly derate the device with respect to its voltage rating. In cases where a failure could very significantly affect system availability, it is not unusual to see deratings of 2.5 to 3 or more applied to the voltage rating of a device. For example, in a system where the nominal DC voltage is 2 kV, one might see the specification voltage rating on the solid-state device to be 5 kV or more.

The switching characteristics are related to the power electronics device's current and voltage ratings, but must also consider the nature of the load that the inverter drives and the desired switching speed of the device. For example, an LSM is a highly inductive load and imposes on the inverter conditions of simultaneous high voltage and high current during the interval when the device is switching from its *on* state to its *off* state. This is sometimes referred to as the turn-off switching transient state. Transistor manufacturers usually provide safe operating area (SOA) data as part of a device's specifications. The SOA describes the voltage-current area where a device can safely operate during the switching condition. For low voltage devices, where the voltage does not exceed a few hundred volts, the SOA is usually a rectangular area with its corners set at the device's ratings or at multiples of the device's ratings. For almost all transistor devices with voltage ratings approaching 1 kV or more, the SOA is not a rectangle. It has an area that is rectangular only in the low-current–low-voltage region, but the high-voltage–high-current region is triangular. An example of the SOA for a high voltage IGBT is shown in Figure C2. For many inverter applications, the SOA requirement becomes the principal application constraint.

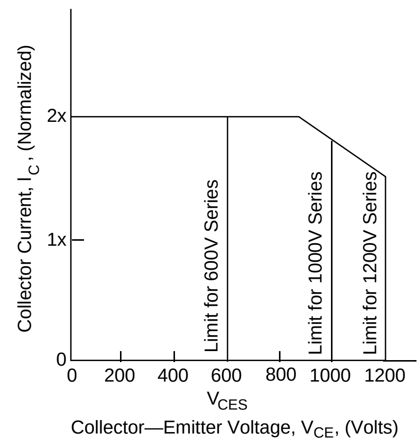

Figure C2. Typical turn-off switching SOA for IGBT devices.

C.2.3 Comments on the Foster-Miller concept for the LCLSM

The concept for the LCLSM is described in the Foster-Miller final report to the FRA (Foster-Miller 1992a). Figure C3 is the electrical schematic for the drive module for one propulsion coil pair. The module consists of a single-phase H-bridge with two IGBT devices connected in series per bridge leg and with regenerative diodes connected across each IGBTB. The regenerative diodes serve a dual function. For operation in the propulsion mode, the diodes provide a path for the phase shift current flow caused by the reactive load of the LSM winding. In the braking mode, the diodes form the path for current to be returned to the DC bus. Comments on the Foster-Miller concept for several key areas follow.

C.2.4 Power electronic device selection for the LCLSM

Foster-Miller rejected the use of the GTO because of its switching speed limitations

The GTO device, as far as its voltage and current ratings are concerned, is more than adequate for its use in the LCLSM. Its use would enable the DC bus voltage to operate at a much higher voltage level than the 2 kV, which is currently envisioned by Foster-Miller. However, the GTO switching speed capability limits its use to an inverter that operates at switching speeds of only a few kilohertz. This device was dropped from consideration by Foster-Miller because of the switching

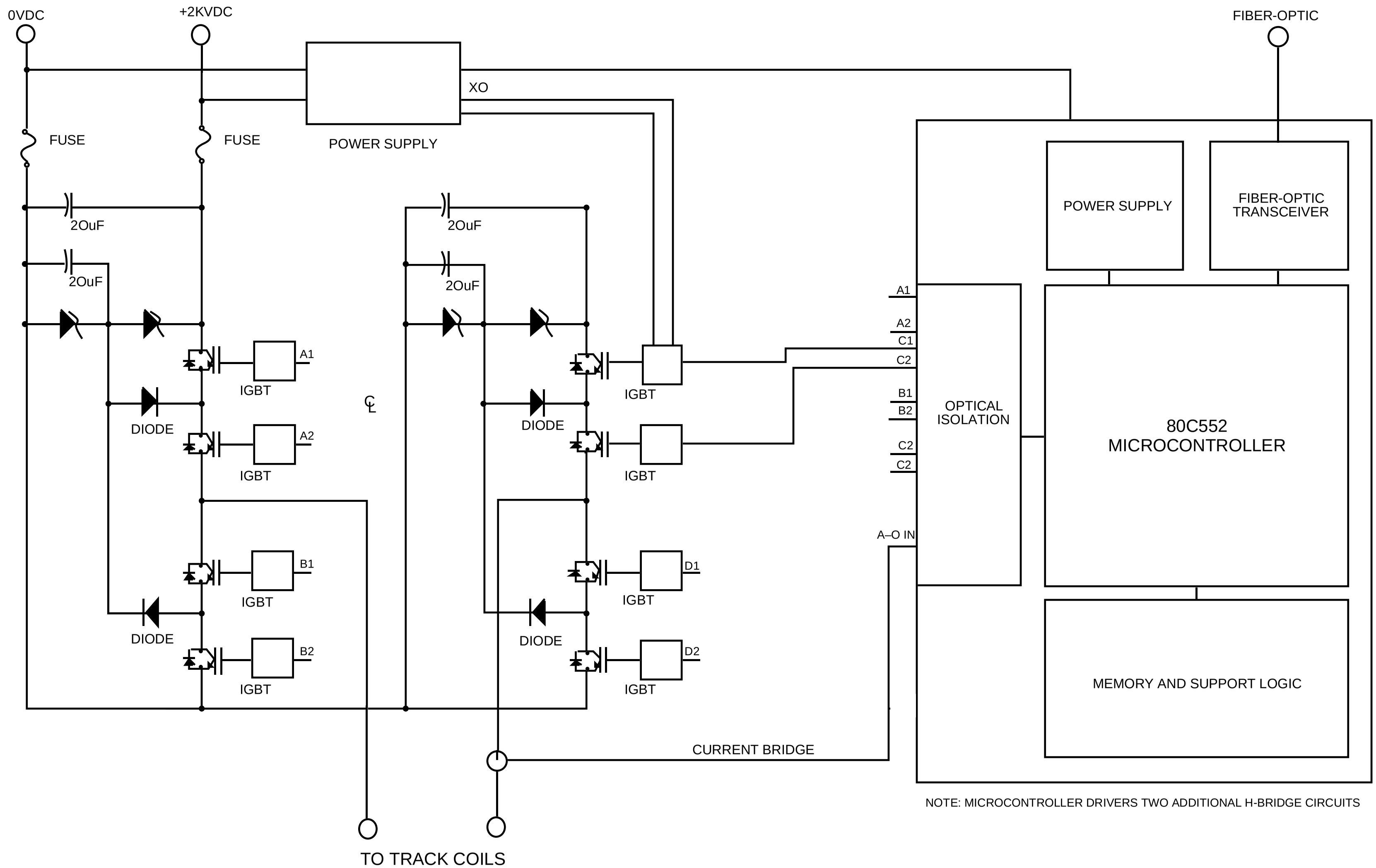

Figure C3. Electronic schematic of Foster-Miller's IGBT module.

speed limitation and the need envisioned by them for operating the H-bridge inverter at a frequency on the order of 10 kHz.

Foster-Miller selected the IGBT as the switching device of choice

The IGBT is the only available transistor device capable of approaching the LCLSM requirements. Since its relatively recent introduction, both its voltage and current capability continue to increase. However, present single devices do not have adequate current and voltage capacity, and series and parallel strings of devices must be considered. The availability of future devices with sufficient current capacity to eliminate the need for parallel devices is likely. Having sufficient voltage ratings to eliminate or reduce the number of series devices is less certain.

A key question is, can we maintain acceptable system operation with failed bridges? An overvoltage condition that causes a bridge to fail will also likely cause several bridges to fail in the immediate area of the surge, unless sufficient voltage derating is provided.

Foster-Miller has stated that the MCT device may become the future device of choice for the LCLSM

The MCT is just reaching commercial availability and the initial devices that are now being introduced will have ratings of about 75 A at 600 V. It is unclear at this time what direction the MCT will take with respect to current–voltage capability, although operating these devices at several kilovolts is now being investigated. If a widespread market with needs similar to the current, voltage, and switching speed requirements of the LCLSM materializes, the MCT could conceivably meet the LCLSM need.

C.2.5 DC voltage distribution system

Foster-Miller selected 2 kV DC as the distribution voltage to the H-bridge inverters. The selection of the distribution voltage is somewhat interdependent with the device technology used in the H-bridge inverters. However, the magnitude of the power called for is quite large for a 2-kV supply. For example, Foster-Miller's eight-car consist is sized at 30 MW for acceleration performance; this results in the requirement for large feeder cables and relatively close substation spacings. The DC distribution voltage level on a power rating basis alone should be much higher than the 2 kV initially selected and perhaps should be as high as 5 to 6 kV. Operation at voltages as high as 6 kV is still within the capability of commercial DC switchgear.

C.2.6 Estimated costs for the IGBT H-bridge inverter

Foster-Miller estimated the 1994 cost for the inverter at $5181 and the breakdown is given in Table C2, which is taken from Table 9–18 of the Foster-Miller (1992a) concept definition report. The cost of the components listed in the table represent reasonable 1994 cost estimates. However, the estimate of $5181 could be understated by as much as $2300 per inverter. The understated costs result from either missing components, or in the case of the IGBT, the listing of the incorrect number of components required. Missing from the list are the components that are required to complete the protection and sensing functions for the inverter and its control circuits.

C.2.7 IGBT device selection

The need for having sufficient DC voltage ratings in conjunction with the estimated 800-A requirement for the IGBTs would most likely

Table C2. Present-day costs for IGBT discrete component (after Foster-Miller 1992a).

Item	*Quantity*	*Description*	*Manufacturer*	*Part no.*	*Cost each ($)*	*Total cost ($)*
1	4	IGBT module	Powerex	CM200DY-24E	199.93	800
2	1	Module heat sink	EG&G	510-12-M	58.75	59
3	4	Clamp diodes	IR	IRKEL132-14s20	46.15	185
4	4	Gate drive modules	Custom	N / A	295.00	1180
5	8	Capacitors	LCC	2M1FPG66X0105J	50.00	400
6	1	Controller	Custom	N / A	300.00	300
7	1	Misc. hardware	Custom	N / A	250.00	250
8	1	Enclosure	Custom	N / A	453.30	453
				Material at 70% of labor		3626
				Labor at 30% of total		1554
				Total		5181

require doubling the number of IGBTs per bridge. The Foster-Miller concept is based on a series-connected dual-device power module component per bridge leg as shown in Figure C3. However, achieving an adequate voltage margin in conjunction with the needed current rating is most likely going to require high-current single-device modules connected in series.

Using a single-device module seems to be more consistent with current developments in the IGBT than the extension of the dual device component considered by Foster-Miller. For example, both Powerex and Fuji have recently introduced 600-A, 1400-V single device power modules, and achieving devices with 800-A capabilities is quite likely in the near future. The higher current ratings are obtained by paralleling more of the lower current devices at the die level of fabrication.

As previously described, a dual-device module is typically made by having the parallel IGBTs mounted on each side of the substrate. Until mounting substrates with higher dielectric strengths become commercially available, the voltage ratings of the module will continue to be limited.

The cost of the IGBT module should be increased from the $800 value cited by Foster-Miller to $1600 to account for doubling the number of devices required.

C.2.8 Missing components for protection and control

Not included in the Foster-Miller cost estimate are the components necessary for current and voltage sensing needed for control and protection, current limiting reactances in the DC link-to-limit fault currents, and EMI filters for control of electromagnetic noise emissions. These components are estimated to cost an additional $1500 per inverter.

C.2.9 Estimated costs for the IGBT integrated module costs

The cost estimated by Foster-Miller for the integrated module is $529 and is summarized in Table C3, which is from Table 9-19 of the Foster-Miller (1992a) concept definition report. Correcting this table for some of the missing components would probably add an additional $400 to the estimated cost, making it approximately $930. Foster-Miller's rationale for their estimate was to use the analogy to the cost savings of consumer electronics resulting from very large scale production. The example used by Foster-Miller was the

Table C3. Estimated costs for IGBT integrated module (after Foster-Miller 1992a).

Item	*Description*	*Factor (%)*	*Cost ($)*
1	IGBT module	10	80
2	Module heat sink	50	29
3	Clamp diodes	25	46
4	Gate drive modules	3	35
5	Capacitors	30	120
6	Controller	5	15
7	Misc. hardware	10	25
8	Enclosure	5	23
	Labor	10	155
		Total	529

television set, where they estimated production quantities of 5 million sets per year. For an LCLSM maglev application, FMI estimated a requirement for about 1.1 million inverters for a dual guideway of 480 km (300 miles) as the rationale for the production scale similarity.

Historically, semiconductor equipment has been experiencing about a 15% cost reduction per year. This has been based on both market growth as well as improvements in manufacturing processes. Beyond this historical basis, it is very speculative to attempt with any confidence to estimate or attempt to verify the anticipated cost reductions that have been put forth by Foster-Miller for the H-Bridge inverter in the quantity scale anticipated. However, having stated that, we can make the following comments about these anticipated cost reductions.

Construction time for a 480-km guideway is likely to be 4 years or more. The 1.1 million inverters estimated by Foster-Miller gives a requirement of nearly 275,000 inverters per year. This is about 5% of the annual production of TV sets. Further, the majority of electronics used in TV sets are also used in other consumer electronics, as well as for automotive electronics, thus resulting in comparative production scales that are greatly beyond that estimated for the LCLSM.

The consumer electronics and the automotive electronics industries are very large and highly competitive businesses. This allows production scales that enable major companies to control and, in many instances, own sources of materiel, manufacturing plants, and integrated manufacturing facilities, and to use other factors that enable lowest cost production. It is unclear the extent to which that situation can be translated to the more limited mass transportation industry.

The principal components of the IGBT inverter—IGBTs, diodes, capacitors, and inductors—are high voltage or high current units, or both, and are not the type of devices that are commonly found in consumer electronics. Traction applications similar to maglev, for example, mass transit and railroads, appear to be the only analogy to the LCLSM inverter. This is true even with the emerging electric vehicle market, where the expected operating voltages will only be a few hundred volts (IEEE 1992). Any projections on cost savings should be addressing potential growth in the high power traction market. In fact, maglev could be one of the major drivers for the technology for that market.

Current world-wide production of transistor power modules is estimated to be about 600,000 modules per month.* This includes both BJT and IGBT modules and includes devices with current ratings that vary from 8 to 800 A. The bulk of the present demand is for devices of the lower current ratings rather than those for the higher current ratings. Of this quantity, only about 20%, or about 120,000 modules per month, are currently IGBTs; the rest are conventional BJTs. The IGBT portion is expected to grow as time goes on. On the basis of Foster-Miller's quantity estimate above, and the 4-year production period for the 480-km dual guideway, the requirement for LCLSM modules would be in excess of 180,000 IGBT modules per month. This not only exceeds current IGBT production, but is also a significant portion of the total monthly production of transistor modules.

Several semiconductor manufacturers have said that the capital cost investment needed to satisfy the LCLSM inverter requirement alone is of the order of 500 to 800 million dollars. This includes the device fabrication, processing, and assembly facilities needed to produce just the power semiconductors for the inverter. Some portion of this investment would probably have to be carried as a cost by a major maglev construction project, absent the need for any other major use of the facilities.

To arrive at some of idea of the potential impact, assume that 50% of the investment would have to be carried by a major maglev construction project and that, further, it is the first 480-km project that bears this cost. This assumption leads to an inverter cost increment of about $300 for each, which has to be added to the other cost elements of the inverter. Foster-Miller's estimate for the IGBT Integrated Module of $530, corrected to $930 to account for the missing components, would then have to be increased to $1330 per module to allow for the amortization of the incremental capital cost requirements.

Similar capital cost arguments could be made for the other major components of the module. Some of these components, such as inductors and EMI filters, may have to be uniquely configured to the IGBT module and, as a consequence, also require significant one-time costs that would also have to be amortized.

The above assumptions only illustrate some of the factors that would influence cost. A more detailed study would be necessary to more accurately determine the cost scaling reductions and the impact of significant capital cost requirements to meet production capacity requirements.

A likely price for the LCLSM power electronics is in the range of $1000 to $1200 per inverter. This is for very high production quantities with a significantly sustained production schedule. This assumes that the economies of scale postulated by Foster-Miller are realized and that the capital costs of increasing production capacity for the solid-state devices does not have to be carried by the maglev project.

C.2.10 Estimated number of power semiconductors required for LSM blocklength systems

GTOs have been identified as the principal power semiconductor by the other SCD studies that make use of conventional blocklength LSMs. The following is a preliminary assessment of the availability of GTOs to satisfy a major maglev construction requirement. It is intended as a point of comparison to the IGBT situation for the LCLSM.

As stated above, the major present use of GTOs includes traction applications and utility medium voltage level (13.8-kV) motor drives. Present production of GTOs is about 7000 per month and includes GTOs in the 4500-V, 2000 to 3000-A ratings that would be typical of a maglev requirement. A representative from Toshiba, a major supplier of traction type GTOs, stated that current production rates are well below available manufacturing capacity. *

* Personal communication with J. Mathis of Collmer Semiconductor, Inc., U.S. representative for Fuji Electric Co.

* Personal communication with G. Ward, Toshiba Electric Co.

Let's use the same 480-km route, 48-month construction example as described above for the IGBT assessment. Typical inverter station spacings would be about every 4 km, thus requiring about 120 inverter stations for the route. Depending upon the particular SCD LSM blocklength concept, an inverter station would require from 24 to 48 GTOs per station. Using the 48 GTOs per station as the example requirement results in a requirement of 120 GTOs per month. This requirement is slightly less than 2% of the present monthly production of GTOs. In the next few years, the traction market in Europe and in third world countries is expected to significantly grow, thus increasing the production output of GTOs. Therefore, a maglev requirement for GTOs for the blocklength concept does not appear to materially affect the availability of GTO devices.

C.3 CONCLUSIONS AND RECOMMENDATIONS

C.3.1 Technical viability

The LCLSM could become a significantly innovative propulsion system. Some of its principal potential advantages over the more conventional blocklength LSM are the improved efficiency and power factor resulting from only the LSM propulsion coils of a maglev consist length being energized at any given time. Guideway to vehicle power transfer using those LSM coils between vehicle bogies as part of an air-core transformer enhances the potential for this concept. Perhaps the most significant possible advantage for the LCLSM concept is its potential for providing propulsion when it is degraded, with some of the LSM windings inoperative. The degree of degradation would of course depend on the number of LSM windings that are disabled. This is in contrast to the blocklength LSM, where a failed LSM winding could disable the entire block and either stop the system or severely curtail operation until it is repaired.

There are many questions that must be addressed to establish the technical viability of the LCLSM. These include questions of the ability to control acceleration, velocity, and lateral stability. Lateral stability may be of concern, as the currently configured LCLSM also provides the lateral guidance forces.

The LCLSM concept operates with all of the LSM coils electrically connected in parallel and the question of the degree of equal current sharing in the bridge inverters is an important issue. In addition, there is a possible stability question. For example, if the degree of current sharing in the inverters is such that the most forward bogies are not conducting as much current as the rearmost bogies, how will this influence lateral stability?

The LSM coils are individually controlled by inverters controlling single coil pairs and will operate in a way that is similar to a single-phase motor or perhaps analogously to a DC stepper motor. This raises the question of potential thrust variations (sometimes referred to as cogging) and how this might adversely affect ride comfort.

Another area of concern is the overall effectiveness of the power transfer concept. Its effectiveness depends critically on obtaining a high degree of coupling between the guideway primary coils and the vehicle secondary coils. A choice of lower modulation frequencies for the inverter is compatible with the LCLSM operating in the propulsion mode, as the LSM frequency is quite low. To what extent would power transfer capability be compromised with the lower switching frequency?

The choice of the 2-kV DC system for power distribution is recognized to be intrinsically connected to the inverter device technology selected. However, for the power levels envisioned for operating multiple car consists, such as the eight-car consist, the tentative selection of 2-kV DC may be a too low a voltage to use. Its choice requires the relatively close DC rectifier station spacings that are similar to those of transit systems and further requires large feeder cables to minimize voltage drop and energy losses. It is not apparent that any trade study was ever conducted on the selection of the DC voltage level.

C.3.2 Economic viability

The relative economics of the LCLSM depend very heavily on the progress of ongoing developments in power electronics devices and the development of the LCLSM probably won't directly influence device costs. However, a serious commitment to maglev development could be one of the major drivers in the development of power electronics devices in much the same way that electric traction requirements for both transit and railroads have pushed the development of GTOs.

The historical trend in the costs of electronics, including power electronics devices, has been downward and there is no reason to think that this trend will reverse in the foreseeable future. The eventual success of the LCLSM will depend quite heavily on this trend continuing and eventually pushing inverter costs into the commodity cost category.

C.3.3 Recommendations

We recommend that an experimental development program be started on the LCLSM, with the emphasis on the power electronics part of the system and controllability issues. A small-scale model development and evaluation study could address almost all of the issues discussed here. It could also address some of the more subtle issues of switching frequencies, waveform synthesis, and polyphase vs. single-phase performance, to name a few. Answers to these questions could provide some direction in the development that might lead to an easing of some of the known economic constraints.

We also recommend that further analysis be done on the selection of the best DC voltage distribution system for the LCLSM. For example, what would be the potential cost savings for a 4-kV or a 6-kV DC system or possibly an even higher distribution voltage? What would the development requirements be, if any, to achieve these expected savings? To what extent, if any, would this affect the selection and configuration of the power electronics and the LSM propulsion coils?

GLOSSARY

AT	Ampere turns.
ANL	Argonne National Laboratory.
BAA	Broad Agency Announcement. A notice from the Government that requests scientific or research proposals from private firms concerning certain areas of interest to the Government. The proposals submitted by private firms may lead to contracts.
BJT	Bipolar transistor.
bogie	Railroad car or locomotive undercarriage.
commutate	Reverse the direction of an alternating current each half cycle to yield a unidirectional current.
consist	Composition (number and specific identity) of individual units of a train.
CGS	Continuous sheet guideway.
cryogenics	Science of low temperature phenomena.
cryostat	Device for maintaining constant low temperature.
DG	Design goals.
DOE	U.S. Department of Energy.
DLF	Dynamic load factor.
USDOT	U.S. Department of Transportation.
EDS	Electrodynamic suspension.
EMS	Electromagnetic suspension.
Emsland	Test site of the TR07 in Germany.
EI	Energy intensity.
EM	Electromagnetic.
FHWA	U.S. Federal Highway Administration.
FRP	Fiber reinforced plastic—polymer-based alternative to ferrous reinforcement of concrete and other materials.
FRA	U.S. Federal Railroad Administration.
GMSA	Government Maglev System Assessment.
guideway	Riding surface (including support structure) that physically guides vehicles specially designed to travel on it.
GTO	Gate turnoff thyristors.
H-bridge	Four-arm, alternating current bridge, the balance of which varies with electrical frequency.
headway	Interval between the passing of the front ends of successive vehicles moving in the same direction along the same lane, track, or other guideway.
HSGT	High speed ground transportation.

HSR	High speed rail.
HSST	High speed surface transportation.
ICE	Intercity Express (German high-speed train).
IGBT	Insulated gate bipolar transistors.
invertor	Electrical circuit device that reverses an input to an opposite output in terms of some electrical characteristics, such as polarity, voltage, or frequency.
JNR	Japanese National Railway.
LCLSM	Locally commutated linear synchronous motor.
levitation	Rise or cause to rise into air and float in apparent defiance of gravity.
levitation, magnetic	Support technology that keeps a vehicle separated from its guideway by riding a surface of magnetic force.
life cycle	Useful or total productive life of an asset or system.
life cycle cost	Present value total cost for acquisition and operation over the useful life of an asset or system.
IEEE	Institute of Electrical and Electronics Engineers.
long-stator	Propulsion using an electrically powered linear motor winding in the guideway.
LSM	Linear synchronous motor.
maglev	Magnetic levitation.
MOSFET	Metal oxide field effect transistor.
magnetic levitation	Support technology that keeps a vehicle separated from its guideway by riding a surface of magnetic force.
MLU	Japanese maglev system employing a U-shaped guideway.
MCT	MOS controlled thyristor.
MR	Minimum requirements.
NMI	National Maglev Initiative.
OCS	Overhead catenary system.
pantograph	Device for collecting current from an overhead conductor, characterized by a hinged vertical arm operating by springs or compressed air and a wide, horizontal contact surface that glides along the wire.
PI	Point of intersection.
PSE	Paris-Sud-EST or Paris-Lyon Route on which the TGV has been in service since 1981 in France.
ROW	Right-of-way—A general term denoting land, property, or interest therein, usually in a strip, acquired for or devoted to transportation.
R&D	Research and development.

SB	Seated and belted criteria.
SCD-FRP	System concept definition, request for proposal
SOA	Safe operating area (electronics).
SST	Severe segment test route.
SRI	Stanford Research Institute.
stator	Nonrotating part of the magnetic structure in an induction motor.
superconductivity	Abrupt and total disappearance of resistance to direct current that occurs in some materials at temperatures near to or somewhat above absolute zero (such as 90 K for some high temperature superconductors).
superelevated curves	Banked curves.
TGV	Train à Grande Vitesse.
Transrapid (TR07)	German high speed maglev system. This system is nearest to commercial readiness.
TSC	Transportation Services Center.
USACE	United States Army Corps of Engineers.
VNTSC	Volpe National Transportation Systems Center.
SP	Standard passenger.
SSTSIM	Severe segment test route simulator.
SCR	Silicon controlled rectifier.
SNCF	French National Railways.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
October 1998

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Technical Assessment of Maglev System Concepts
Final Report by the Government Maglev System Assessment Team

5. FUNDING NUMBERS

6. AUTHORS
James H. Lever, Editor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
Special Report 98-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Maglev Initiative, U.S. Department of Transportation, U.S. Army Corps of Engineers, U.S. Department of Energy, and Argonne National Laboratory

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
For conversion of SI units to non-SI units of measurement, consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units*, published by the American Society for Testing and Materials, 100 Barr Harbor Drive., West Conshohocken, Pennsylvania 19428-2959.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The Government Maglev System Assessment Team operated from 1991 to 1993 as part of the National Maglev Initiative. They assessed the technical viability of four U.S. maglev system concepts, using the French TGV high-speed train and the German TR07 maglev system as assessment baselines. Maglev in general offers advantages that include high speed potential, excellent system control, high capacity, low energy consumption, low maintenance, modest land requirements, low operating costs, and ability to meet a variety of transportation missions. Further, the U.S. maglev concepts could provide superior performance to TR07 for similar cost or similar performance for less cost. They also could achieve both lower trip times and lower energy consumption along typical U.S. routes. These advantages result generally from the use of large-gap magnetic suspensions, more powerful linear synchronous motors and tilting vehicles. Innovative concepts for motors, guideways, suspension, and superconducting magnets all contribute to a potential for superior long-term performance of U.S. maglev systems compared with TGV and TR07.

14. SUBJECT TERMS
High-speed ground transportation
High-speed trains
Maglev
Magnetic levitation

15. NUMBER OF PAGES
241

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL