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MAGLEV SYSTEM CONCEPT USING 20-K HIGH-TEMPERATURE SUPERCONDUCTORS AND HYPERCONDUCTORS*

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MAGLEV SYSTEM CONCEPT USING 20-K HIGH-TEMPERATURE SUPERCONDUCTORS AND HYPERCONDUCTORS

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ABSTRACT

A magnetically levitated high-speed ground transportation concept is proposed that uses high-temperature superconductors or hyperconductors, cooled by liquid hydrogen at 20 K, to provide levitation. An on-board hydrogen-powered turbine/generator provides electricity for propulsion by linear induction motors. The liquid hydrogen is used to cool the superconductors and the windings of the generator and motors before combusting in the turbine. The principal advantage of this system is the potential to greatly reduce the cost of the guideway, which is completely passive.

1. INTRODUCTION

Magnetically levitated (maglev) high-speed ground transportation has the potential to benefit the overall transportation infrastructure, provide more energy-efficient transportation, reduce the environmental effects of transportation, and reduce dependency on foreign energy supplies. Traveling at approximately 500 km/h (300 mi/h) for distances of up to about 960 km (600 mi), initial maglev systems will most likely operate between hub airports of major cities [1]. It is expected that both airport and highway congestion will be reduced as a result of successful implementation of this technology.

A major factor in the eventual incorporation of maglev technology into the transportation sector will be the achievement of a low system capital cost. One of the largest cost components of maglev is the guideway, and in most system concepts a substantial fraction of this cost would be incurred in providing large amounts of electrical power along the guideway to propel the vehicle. In this paper, we explore the advantages and disadvantages of a specific maglev concept that eliminates this requirement.

2. SYSTEM CONCEPT

The maglev concept discussed here uses electrodynamic suspension (EDS), in which repulsive levitation forces are produced between superconducting magnets (SCMs) aboard the vehicle and "image magnets" produced by eddy currents induced in a conducting guideway by the moving superconducting magnets. Typical of this method, inherently stable levitation can be achieved with relatively large guideway clearance, but conventional wheel-on-rail support must be used at low speeds. The major advantage realized by the large clearance is larger tolerance values in the guideway, resulting in lower capital and maintenance costs.

In our concept, the vehicle levitation magnets are made from liquid-hydrogen-cooled high-temperature superconductors (HTSs) operating in the persistent-current mode. The vehicle carries a large storage tank of liquid hydrogen but no refrigerator. The vehicle is propelled by a short-stator single-sided linear induction motor (LIM) that interacts with the guideway. Instead of a LIM, a short-stator linear homopolar synchronous motor (LHSM) could be used, and this option is discussed later in the paper. Electrical power is provided to the LIM from an on-board generator driven by an air-breathing liquid-hydrogen turbine. The guideway is supported by a concrete structure and is divided into a levitation portion, which consists of a continuous aluminum sheet, and a separate propulsion portion, which consists of a continuous aluminum sheet backed by an iron strip.

The flow of fluids (and electricity) in the system is shown schematically in Fig. 1. Small amounts of liquid hydrogen flow as needed from the storage tank to cool the levitation magnets and the windings of the LIM and generator. After cooling these components, the hydrogen passes into the turbine and combusts with ambient air to provide the motive force for the turbine. Typically, the amount of hydrogen required for propulsion is larger than that required for cooling, and the bulk of the hydrogen flow to the turbine is provided by a direct line. The turbine exhaust consists mainly of water and oxygen-depleted air.

There is also the possibility of using liquid-hydrogen-cooled hyperconductors (normal conductors with extremely low resistivity) for the levitation magnets. The advantage is that the magnets can be deenergized at low speeds and in the stations. This reduces energy losses and also eliminates the effect of external magnetic fields on people in the vicinity of the station.

3. STATUS OF KEY TECHNOLOGIES

The proposed maglev concept uses several technologies that are still under development. However, as shown below, each key-component technology may be available in the near term, given present development rates.

3.1. Maglev

Contact-free maglev systems have been under development for many years for use in low- and high-speed ground transportation systems. Several existing prototype maglev systems, such as the German Transrapid and M-Bahn, Japanese MLU and HSST, and British Birmingham maglev, have successfully demonstrated their unique characteristics and potential advantages over many conventional transportation systems [1].

3.2. High-Temperature Superconductors

Since the discovery of superconductors with critical temperatures above the boiling point of liquid nitrogen [2], rapid progress has been made in evolving these HTSs into

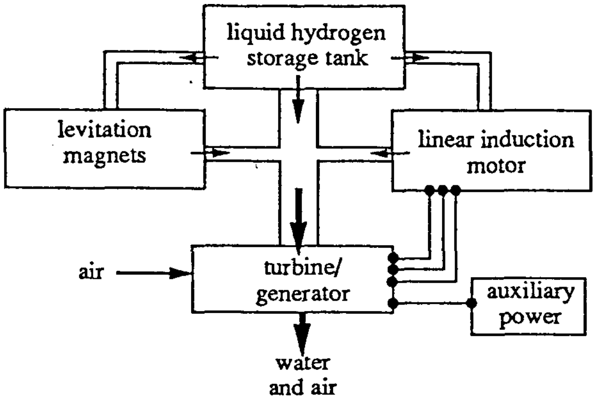

Fig. 1. Schematic of fluid and electrical power flow in the liquid-hydrogen maglev system.

practical magnet wire. One important advance was the discovery that the Bi-Sr-Ca-Cu-O compound, when processed with powder-in-tube techniques, exhibits useful critical current densities in liquid helium (LHe) at 4.2 K in magnetic fields greater than 20 T [3]. Recent developments [4, 5] with this type of HTS have produced short samples of wire with current densities well in excess of 100 A/mm^2 in magnetic fields of 5 T and an operating temperature of 20 K. Such performance would be satisfactory for maglev systems, and these superconductors could be cooled by liquid hydrogen, which boils at 20 K at ambient pressure.

Because heat capacity increases rapidly with temperature at cryogenic temperatures, the 20-K HTSs should be inherently more stable and less subject to quench than conventional superconductors operating at 4 K. So far, the required current densities in these wires have only been obtained in short samples. However, research on this type of wire is proceeding at many laboratories throughout the world, and it seems likely that production processes will be developed in the near future for making long lengths of the HTS with the required properties.

3.3 Hyperconductors

An alternative to HTSs for the proposed system is high-purity aluminum conductors that have extremely low resistivity at 20 K. These hyperconductors have received extensive development in recent years and are considered viable alternatives to superconductors for many applications [6]. The hyperconductors could be used as primary windings in the LIM and as field and armature windings in the generator. They could perhaps also be used for the levitation magnets, however, the magnets would then require continuous power when energized.

3.4. Liquid Hydrogen

Mainly because of activity in the space transport sector, the ability to handle liquid hydrogen has advanced significantly in recent years, and in several industrialized countries the option to convert part or all of the transportation fleet to hydrogen is in the experimental and evaluation stages. Large quantities of liquid hydrogen are now shipped by truck, insulated storage containers have been approved for installation in automobiles that operate on public highways, and filling and refilling operations have been standardized and made as safe as petroleum-based technology [7]. Because of hydrogen's tendency to rise in the atmosphere, it is actually considered safer for many applications than gasolene or propane in accident scenarios [7].

One of the remaining difficulties with liquid-hydrogen technology is the relatively short lifetimes of existing hydrogen pumps, mainly due to tribological problems at 20 K. Conventional magnetic bearings are one of many possible options to solve this problem. There is also a good possibility that HTS magnetic bearings could provide reliable operation and the long lifetimes required [8].

3.5. Turbine/Generator

In the United States, liquid-hydrogen turbines have been under development since the mid-1950s, and successful prototypes have been demonstrated [9, 10]. A number of experimental generators using superconductors cooled in LHe have been operated at power levels of tens of MVA [11]. One generator design uses hyperconductors cooled by liquid hydrogen [12].

4. ADVANTAGES COMPARED WITH EXISTING MAGLEV SYSTEMS

The Japanese maglev system, MLU, is characterized by its EDS, null-flux magnetic guidance, and long-stator air-cored linear synchronous motor propulsion [13]. This system, using LHe-cooled SCMs without levitation control, has many advantages over other systems. In particular, the larger levitation air-gap can reduce guideway construction and maintenance costs. The German Transrapid maglev, levitated by an electromagnetic suspension (EMS) with active feedback and propelled by long-stator iron-cored linear synchronous motors, has demonstrated high overall operation efficiency, low harmful magnetic fields inside the passenger area, high reliability, and good ride comfort [14]. The Japanese EMS system, HSST, is levitated by attractive magnets and propelled by on-board short-stator LIMs [15]. A significant feature of the HSST system is the use of a simple passive guideway. The M-Bahn and Birmingham maglevs are low-speed systems that can provide low-noise and pollution-free transit services within cities and towns [1].

Each existing maglev system also has its own disadvantages. One of the largest cost components is the active guideway. Both the Japanese MLU and German Transrapid use an active guideway in the form of a long-stator propulsion, in which the guideway is divided into many motor sections and energized section-by-section as the vehicle moves forward. The length of the motor sections is limited by the power factor and the efficiency of the propulsion system; length is about 300-2000 m for Transrapid and 42 m for MLU. In most long-stator propulsion systems, a substantial cost results from the need to provide power distribution and power switching along the whole length of the guideway, as well as control and position-detection systems along the guideway to detect vehicle position and switch power from one section to another.

Propulsion in the Japanese HSST maglev system is provided by short-stator LIMs aboard the vehicle. While there is no active guideway, power is delivered to the LIMs via continuously energized cables along the guideway [16]. This system seems to be limited to medium-speed applications because at high speed the power pickup device requires increasing maintenance.

In most EDS systems, the SCMs serve the combined functions of levitation, propulsion, and guidance. Propulsion power is generally proportional to the product of the magnetic field of the SCMs and the current in the guideway. Because the power requirements and cost of an active guideway are roughly proportional to the current, a very large SCM field is desired to keep the guideway current low, and in general the propulsion motor needs a much stronger dc field than does the levitation system. An associated problem in the EDS maglev system may be the need to shield the strong dc magnetic fields generated by the SCMs. This implies that magnetic field shielding problems may be less serious if we can reduce the field strength required by the propulsion system.

The maglev concept described in this paper can overcome some of the shortcomings discussed in the existing systems. A major advantage of the proposed system is that the propulsion and auxiliary power is generated entirely aboard the vehicles. The use of a LIM to propel the vehicle makes it feasible to have a simple passive guideway, eliminating the high capital cost associated with a complicated power distribution, control, and switching system. Because the SCMs located at the end of the vehicle are used only for levitation and guidance, current density in the SCMs is only about one-third that of a conventional EDS maglev system. Thus, a possible advantage is that the magnetic field strengths of the levitation magnets can be reduced, which lessens the difficulty in shielding passengers from these magnetic fields. A further advantage of the system is that cryogenic refrigeration is also passive, eliminating refrigerators aboard the vehicles.

5. SINGLE-CAR VERSUS MULTICAR (TRAIN) OPERATION

Two general modes are possible in a maglev operation. The multicar, or train, mode has many linked vehicles, with the entire assembly powered by a small number of motive vehicles. Such an arrangement benefits from economies of scale related to the power plant. The single-car mode benefits from a system standpoint in that more nonstop destinations may be served more frequently. The weight and power requirements of these two possible system designs are compared in this section through two simplified example designs.

Two major factors that are used to determine the operational model are the aerodynamic drag and the weight of a maglev system per passenger seat. Both factors show that the train operation is favored. The aerodynamic drag F_a of a moving vehicle is [17]

$$F_a = 0.5A\rho v^2(c_1 + c_2L/D) \quad (1)$$

where A is cross-sectional area, L is length, D is hydraulic diameter, ρ is the density of air, v is the vehicle speed, and c_1 and c_2 are the drag coefficients corresponding to the front and side surfaces of a vehicle. The drag coefficients will vary depending on design details, but typical values are $c_1 = 0.15$ and $c_2 = 0.016$. Assuming that vehicle size is always the same, whether operated as a single car or in a train, we calculate the ratio of aerodynamic drag on an n-car train to that of a single vehicle

$$F_{a,n}/F_{a,1} = [1 + nc_2L/(c_1D)]/[1 + c_2L/(c_1D)] \quad (2)$$

For the drag coefficients chosen, $c_2/c_1 \approx 0.1$, and in most maglev designs $L/D \approx 10$. Equation (2) then becomes

$$F_{a,n}/F_{a,1} \approx (1 + n)/2 \quad (3)$$

Thus, for n large, drag per car is reduced by about half, when the car is part of a train.

In the train configuration, power generation is centralized in a power supply car that produces and transmits electricity for hotel functions and power to the LIMs in the other cars in the train. LIMs are located on the power supply car and each passenger car. This decentralization of propulsion reduces the power density of the LIMs and decreases the stresses on the guideway. Because the LIMs are linear in nature, there is only a small scaling benefit as power requirements increase. However, the turbine and generator are volume devices, and specific power increases at larger power ratings. A summary of the major parameters of an example multicar system is shown in Table 1. A typical profile of the forces and the total power required as a function of velocity are shown in Fig. 2. A maximum acceleration of 1.0 m/s^2 is assumed at low speed, with a reserve acceleration of 0.3 m/s^2 at cruising speed. The peak magnetic drag was assumed to be 25% of the levitation force at a critical speed of 5.3 m/s. The estimations are based on the following assumptions: 5-6 W/kg and 4 kW/kg power-to-mass ratio for generator and turbine at about a hundred MW capacity respectively, and 1-2 kW/kg for the propulsion motor at about a 10 MW capacity [18].

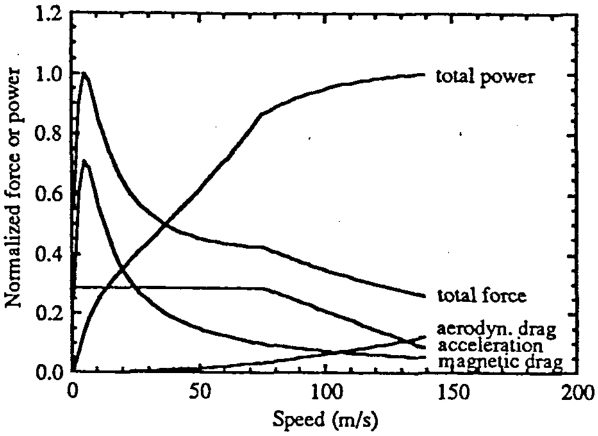

Fig. 2. Normalized power and force of a 10-car maglev as function of vehicle speed. Maximum power is 68 MW and maximum force is 1863 kN.

A summary of parameters for single-car operation is given in Table 2 with the same general assumptions. In this case, the power supply is located in the same vehicle, but its weight is given separately. It is clear that the weight of the system per passenger seat and the power required per passenger seat is larger for the single-car operation than for the multicar operation.

6. PROPULSION

As mentioned before, two promising propulsion schemes may be used in our maglev concept. One is the linear induction motor (LIM) and the other is the linear homopolar synchronous motor (LHSM). Each is characterized by primary windings that are located on the vehicle and energized by on-board power, and their guideways are passive.

LIM propulsion, the simplest system, has several unique features relative to other propulsion systems. The LIM is a highly controllable and reliable machine and its guideway can be as simple as a conducting plate with iron backing. We may expect low construction and maintenance costs. Detailed design and analysis of LIMs can be found in many papers, (e.g. 19, 20]).

The double-sided LIM and the single-sided LIM are the most commonly discussed short-stator LIMs for maglev propulsion. The double-sided LIM has the reaction rail mounted vertically between two opposed motor primaries and

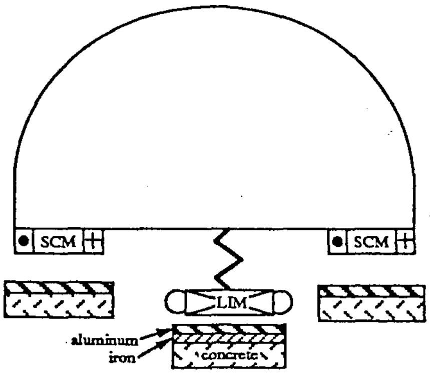

Fig. 3. Schematic of EDS maglev with secondary suspension to adjust LIM gap distance.

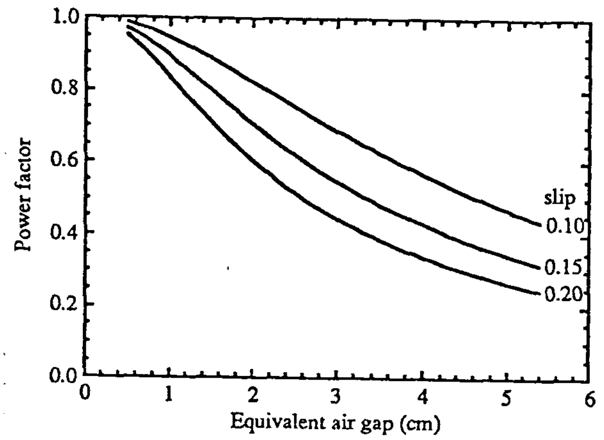

Fig. 4. Power factor of single-sided LIM as function of equivalent air gap with slip as parameter. Other parameters: synchronous speed = 154 m/s, pole pitch = 0.4 m, effective reaction rail thickness = 7 mm, conductivity = 3.0×10^7 S/m.

can produce a higher thrust density but a relatively small normal force. One of the shortcomings of the double-sided LIM is the vertical secondary in the guideway, which presents difficulties at intersections and switching points. The double-sided LIM does not tolerate large disturbances in the horizontal direction, and this can limit the ability to negotiate horizontally with the EDS guidance system. The double-sided LIM may not be suitable to the maglev concept presented in this paper.

In the single-sided LIM, the primary is located above a horizontal reaction rail. The air-gap control and tolerance in a single-sided LIM are not as critical as in a double-sided LIM. The horizontal arrangement of the single-sided LIM allows both horizontal and vertical movement and produces forces that are added to those of the EDS guidance and levitation system. However, for better performance, the LIM air gap should be as small as possible. This conflicts with the desire to use a large levitation gap to decrease the tolerances and hence the cost of the guideway. A possible solution to this problem is the use of a mechanical servo system between the vehicle and the LIM to keep the propulsion air gap as small as possible even if the levitation air gap varies during operation. Such a system is shown schematically in Fig. 3. Because the LIM on each passenger car weighs about 7 tons, this should be feasible. In particular, such a mechanical secondary suspension may be necessary to keep a small propulsion gap at low speeds, because the levitation and guidance gaps may be increased to reduce magnetic drag. In practice, this would typically be accomplished by conventional wheels, which are used to increase the height of the SCMs above the guideway at low speeds until the magnetic drag peak is passed and are then retracted to enable EDS levitation.

When the primary windings of the LIM are made of HTS or hyperconductors, the ohmic losses in the primary windings are negligible. The LIM system efficiency then depends on the resistance of the secondary, or the resistance of the guideway conductors. In this case, the efficiency η of the LIM is approximately equal to the ratio of the vehicle speed v to the synchronous speed v_s, or $\eta = v/v_s = 1\text{-}s$, where s is slip, $s = (v_s - v)/v_s$. The LIM power factor depends on the air gap. Figure 4 shows the power factor as a function of the equivalent air gap (from the center of the primary conductors to the surface of the guideway conductors), with slip as a parameter. It is seen from Fig. 4 that we should keep the air gap as small as possible to reduce reactive power in the system. It follows that is is necessary for the proposed system to have a secondary suspension to keep a small air gap.

One of the major disadvantages of the single-sided LIM is the weight of the iron necessary to minimize the reactive power. One possible alternative to greatly reduce the weight is a double-sided hyperconductor LIM (HLIM), shown in Fig. 5, in which three-phase windings of HTS or 20-K hyperconductor, which form the LIM primary, are sandwiched between two sheets of aluminum, which form the double-sided passive secondary. The advantage of the HTS or hyperconductors is that the lower resistivities enable larger current densities to be used so that higher magnetic field strengths can be generated. This permits a large air gap that is compatible with the EDS guidance system, even when the reaction rails are vertical. The larger air gap will increase the amount of reactive power required from the generator, but the total weight should decrease.

Because the efficiencies of the turbine and generator decrease significantly away from their optimal design point, they usually operate at a fixed frequency. A design option for the power supply includes a variable-frequency power supply that can convert constant-frequency power from the generator to variable-frequency power. LIM performance over the entire velocity range can be greatly improved by using a variable-frequency and variable-voltage power supply. This is especially important for starting conditions, where magnetic drag is high and propulsion efficiency is low. If the total power requirements are dominated by acceleration needs, this increase in efficiency at low speeds will reduce the weight of the LIMs. Based on the use of advanced power electronics technology, gate-turnoff (GTO) thyristors may be used to build the variable-frequency power supply. High voltage (up to 4500 V) and high current (up to 3000 A) are available in commercial GTO thyristors.

Shortcomings of LIMs for maglev propulsion at high speed are the skin effect and dynamical end effect that may reduce LIM efficiency and power factor at high speed. The skin effect may be overcome by using short-circuited windings in the secondary, rather than solid aluminum plate. One of the methods to compensate for the dynamical end effect is the use of compensation windings at the end of the LIM [19].

The LHSM has a typical arrangement in which the field windings and the armature windings are both located on the same ferromagnetic core stator. This makes a passive guideway feasible. Both transverse and longitudinal flux LHSMs can be used. One unique feature of the LHSM is its large normal attractive force. The LHSM can produce adequate

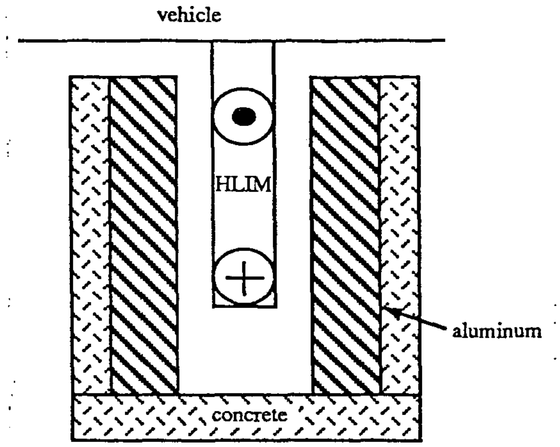

Fig. 5. Schematic of double-sided hyperconductor linear induction motor (HLIM).

propulsion, levitation, and guidance forces simultaneously as an integrated maglev system. In this case, the SCMs for levitation and guidance could be omitted. Design and analyses of this machine are given in the literature [19, 21].

7. DISCUSSION

The SCMs will be used for levitation and guidance but not propulsion. This arrangement can reduce SCM current density. In the example system, four SCMs arranged horizontally at the ends of each car will be sufficient to levitate the vehicle 25 cm above the aluminum sheet guideway (from the center of the SCM to the surface of the sheet). The required SCM current density is about 235 kA-turn in the passenger cars and 398 kA-turn in the power supply car. Current density in the passenger car is only about one-third that in most existing EDS systems. It follows that the new system may have less magnetic field shielding problems.

If hyperconductors are used for the levitation magnets, they will generate joule heating losses. We assume a current density of 20 kA/cm^2 and a resistivity of 13.6 nΩcm, corresponding to a residual resistivity ratio (RRR) of 1530 at a temperature of 25 K and a magnetic field of 4.0 T [22]. For the passenger car, power loss for each magnet is 38.3 kW and 153 kW per car. This corresponds to a 2.25% increase in the total power use in a multicar system, with a similar increase if hyperconductors are used for the guidance magnets. This small increase is only possible for the low currents in the present system. If propulsion is accomplished by an active guideway, then the penalty associated with the use of hyperconductors for levitation and guidance is a 40% increase in power because of the larger currents required. If we assume that hydrogen boiling with a latent heat of 441 J/g carries away the heat from the hyperconductors, then 153 kW of thermal energy requires 345 g/s of hydrogen flow. With a heat of combustion of 121 kJ/g, the chemical energy delivered to the combustor of the turbine from this flow is 42 MW. Even with a relatively low turbine efficiency, this is considerably more power than the ≈7 MW needed to propel the car. If the hyperconductors have RRR = 10,000 and operate at 20 K, the resistivity is 5.5 nΩcm [22]. With a current density of 10 kA/cm^2, the joule heating will then be reduced to 7.7 kW per magnet, and the hydrogen flow needed for cooling will be a much better match to the propulsion requirements.

The use of hydrogen as a fuel produces mainly water as an exhaust product. The hydrogen can be produced by a number of environmentally benign methods. The energy cost of refrigeration to liquify the hydrogen is relatively low compared to the fuel energy of the hydrogen.

Because the turbine is mainly used to generate electricity, it can be enclosed in a sound-absorbing container, and the noise from the turbine/generator should be insignificant compared to the aerodynamic noise of the moving vehicle. It may be possible to use part of the turbine exhaust to provide guidance, improve ride quality, and perhaps provide thrust in emergencies. While hydrogen-powered turbine/generators are not common, the technology is a relatively straightforward extrapolation from conventional turbines.

8. CONCLUSIONS

A proposed maglev concept would use 20-K high-temperature superconductors or hyperconductors, and on-board hydrogen-powered turbine/generator and linear induction motors for propulsion. Before passing to the turbine for combustion, the liquid hydrogen is used to cool the electrical components, so that on-board cryogenic refrigerators for the levitation magnets are eliminated. The principal advantage of this concept is the potential for greatly reducing the cost of the guideway, which is completely passive. Because the levitation magnets are not used for propulsion, the magnetic fields that they generate are lower than those of an EDS maglev with active guideways. The major disadvantage is that the additional weight of the LIMs, turbine and generator must be carried. Weight and power scaling favor multicar trains over single-car systems. Hyperconductors can be used for the levitation and guidance magnets if the residual resistance ratio is about 10,000 and current densities are not higher than about 10 kA/cm^2.

9. ACKNOWLEDGEMENTS

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Table 1 Summary of Parameters for Example MultiCar System

<u>General</u>		
Cruising speed	500 km/h	
Passengers/car	100	
Train operation	10 passenger cars	
	1 power supply car	
Total length	340 m	
Total weight	540 tons	
Weight/seat	0.54 tons	
<u>Passenger Car</u>		
Length	30 m	
Width	3.2 m	
Height	3.5 m	
Weight	42 tons	
<u>Power Supply Car</u>		
Vehicle length	40 m	
Total weight	120 tons	
Generator	25 tons	
Turbine	26 tons	
Liquid hydrogen	5 tons (for one hour operation)	
LIM	20 tons	
Frame + misc.	44 tons	
<u>Levitation Information</u>		
Levitation force	412 kN	for passenger car
	1176 kN	for power supply car
SCM/car	4	(located at ends of car)
SCM length	2 m	
SCM width	1 m	
Levitation height	0.25 m	
SCM current	235 kA-turn	for passenger car
	398 kA-turn	for power supply car
<u>Guidance Information</u>		
SCM/car	4	(located at ends of car)
SCM current	235 kA-turn	
Guidance force	135 kN - at 5-cm shift	
<u>Propulsion</u>		
Total required power	68 MW	
	9.2 MW	for each passenger car
	26 MW	for power supply car
Power per seat	68 kW	

Table 2 Summary of Parameters for Example Single-Car System

<u>General</u>	
Cruising Speed	500 km/h
Passengers	100
Train operation	1 passenger car with power supply
Total length	60 m
Total weight	102 tons
Weight/seat	1.02 tons
<u>Passenger Component</u>	
Length	30 m
Width	3.2 m
Height	3.5 m
Weight	42 tons
<u>Power Component</u>	
Length	30 m
Total weight	60 tons
Generator	19 tons
Turbine	5 tons
Liquid hydrogen	1 ton (for one hour operation)
LIM	10 tons
Frame + misc.	25 tons
<u>Propulsion</u>	
Total required power	14 MW
Power per seat	140 kW