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# **TLV Status Report**

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**METREK Division of The MITRE Corporation**



**October 1977**

## **TECHNICAL REPORT**

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## ABSTRACT

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The purpose of this report is to place the worldwide research efforts in perspective as it addresses the outstanding technical problems as a whole. This will provide the reader with a tool for assessing target areas for future research which complement the ongoing worldwide efforts.

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## ACRONYMS/ABBREVIATIONS

AC	Alternating current
ARGE	Industrial combine of KM and MBB (also called Transrapid-EMS)
CIGGT	Canadian Institute of Guided Ground Transport
CSI	Compressed Superinsulation
DC	Direct current
DLIM	Double-sided linear induction motor
DOT	Department of Transportation
EDS	Electrodynamic system (repulsion maglev, uses superconducting coils)
EMS	Electromagnetic system (attraction maglev, uses DC electro-magnets)
FRA	Federal Railroad Administration
FRP	Fiberglass reinforced plastic
Ge	Germanium
GHe	Gaseous helium
G/P	Guidance/Propulsion
HSGT	High speed ground transportation
ISPS	Integrated suspension propulsion system
JAL	Japan Airline
JNR	Japanese National Railroad
KM	Krauss-Maffei (German industrial firm)
LEM	Linear electric motor
L/G	Lift/Guidance
L/G/P	Lift/Guidance/Propulsion
LHe	Liquid helium
LN <sub>2</sub>	Liquid nitrogen
LIM	Linear induction motor
LSM	Linear synchronous motor
MAGLEV	Magnetic levitation
MBB	Messerschmitt-Bolkow-Blohm (German industrial firm)
MIT	Massachusetts Institute of Technology
MMF	Magnetomotive force
MOT	Ministry of Transportation (Japan)
Nb	Niobium
NCS/P	Non-contact suspension/propulsion
NRC	National Research Council (Canada)
PCU	Power conditioning unit
PHI	Plastic honeycomb insulation
PTACV	Prototype tracked air cushion vehicle
QFAN	Noise suppressed fan
REM	Rotary electric motor
SCM	Superconducting magnet
SLIM	Single-sided linear induction motor
Sn	Tin



# ACRONYMS/ABBREVIATIONS (Concluded)

THL	Tracked Hovercraft Limited
Ta	Tantalum
Tc	Critical temperature of a superconductor
Ti	Titanium
TLRV	Tracked levitated research vehicle
Transrapid-EMS	(See ARGE)
TSC	Transportation Systems Center (DOT/Cambridge, MA)
VVVF	Variable voltage, variable frequency
Zr	Zirconium

## **CHAPTER I**

### **AN OVERVIEW OF WORLDWIDE RESEARCH PROGRAMS ON NONCONTACTING SUSPENSIONS FOR GROUND TRANSPORTATION VEHICLES**

## 1.0 INTRODUCTION

This chapter presents a brief overview of worldwide research programs on noncontacting suspensions for ground transportation vehicles. Basically historical in nature, it provides an introduction to the level of effort expended throughout the world on noncontacting suspension concepts. The intent is not to completely document such research, but to illustrate the extent of the overall, worldwide research effort.

Termed "Tracked Levitated Vehicles" (TLV) in the technical community, noncontacting suspension involves those aspects of advanced ground transportation concepts whereby the vehicle is levitated and guided along a track without making physical contact with it. Applications of this type of suspension are aimed for both high speed (faster than 200 km/hr) and low speed systems (slower than 200 km/hr).

This report is concerned with two major types of noncontacting suspensions - air cushion, where the vehicle is suspended on a pressurized stream of air, and maglev, where the vehicle is suspended by a magnetic field. Section 2 discusses air cushion suspension research in England, France, Germany and the United States. Sections 3 and 4 discuss maglev suspension research in Canada, Germany, Japan and the United States. The attraction maglev concepts discussed in Section 3 concern levitation by means of conventional electromagnets, where attractive magnetic forces are employed between an iron core electromagnet and a rail. The repulsion maglev concepts discussed in Section 4 concern levitation by means of superconducting coils, where repulsive electrodynamic forces are generated by a coil moving

over a conducting (usually aluminum) guideway. The scope of this chapter is confined to these concepts for air cushion and maglev.<sup>1</sup>

The bibliography provides further details concerning the physics and engineering background of these concepts and their associated hardware.

Emphasis in this chapter is given to the larger test facilities that have been constructed to date, although some representative small scale experiments are briefly mentioned. Omissions, primarily in some of the smaller scale experimental or purely theoretical programs, should not be taken to reflect on their potential.

It should be noted that although every effort for accuracy was undertaken, the test program and hardware descriptions presented here are the opinion of The MITRE Corporation and do not necessarily reflect the opinions of the governments or firms which were involved in conducting them.

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<sup>1</sup>These categories are not all-inclusive. Research on other concepts has also been carried out; e.g., the "magnetic river" concept studied at the Imperial College in London, England exhibits repulsion forces, yet utilizes iron core electromagnetics, and the proposed URBA transit system studied at the Lyons Institute of Technology in France uses suction type air cushions for suspension.

## 2.0 AIR CUSHION

This section presents a brief description of the extent of development of air cushion suspension in England, France, West Germany and the United States. The research programs in both France and the United States led to the construction of full scale, commercial prototype vehicles.

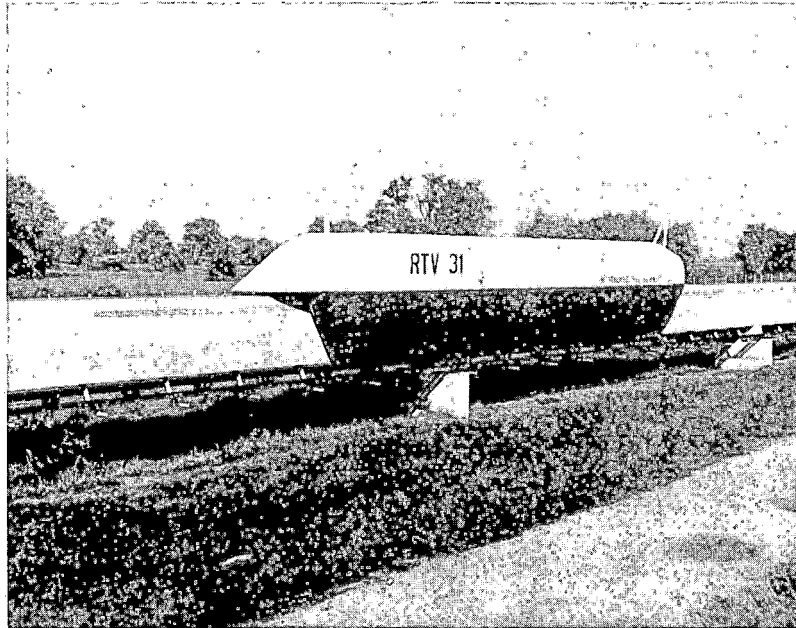
### 2.1 England

In September 1967, Tracked Hovercraft Ltd. (THL) was formed by the British National Research Development Corporation to conduct research and development of the "hovertrain" concept. The RTV 31 shown in Figure 1 was the result of this program. This vehicle was tested to speeds of 172 km/hr on its 1900 m of guideway in January 1973. The RTV31 was purely experimental in nature - not a commercial prototype. There were no provisions for carrying passengers or crew; all control was accomplished from wayside.

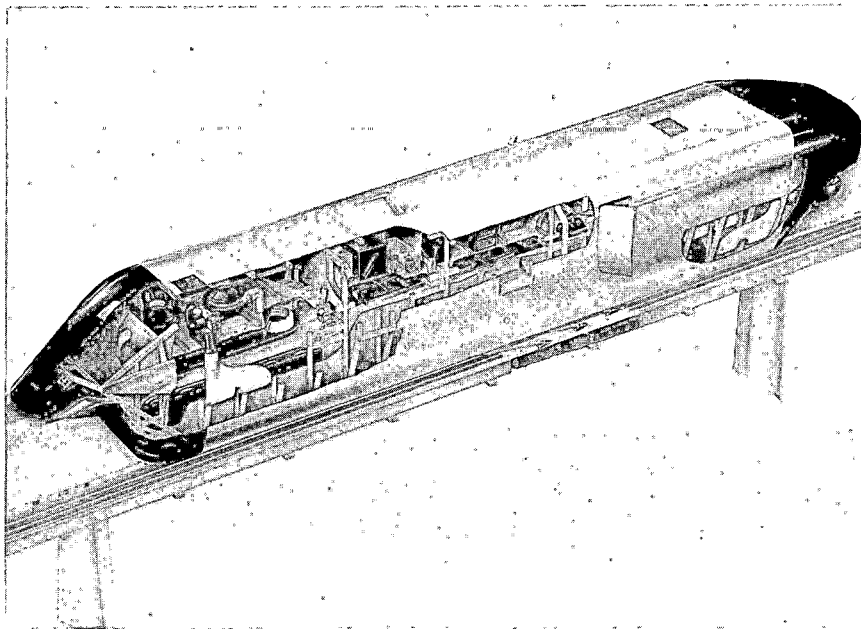
Suspension of this 22.1 m long, 22 ton vehicle was obtained by eight independently sprung peripheral jet air cushions and a guideway of box beam cross section. Propulsion was by a fixed frequency (50 Hz) single sided linear induction motor (SLIM) designed to reach a speed of 67 m/s if three miles of guideway had been completed.

In support of this test program, the following facilities were also constructed:

1. RTV 41 (Figure 2)  
This was a small scale linear test facility with 85.3 m of track used to test small scale LIM designs.
2. Suspension System Testing (Figure 3)  
Full size air cushion "hoverpads" were tested on this dynamic table to confirm the theoretical and practical development of the air cushion suspension.

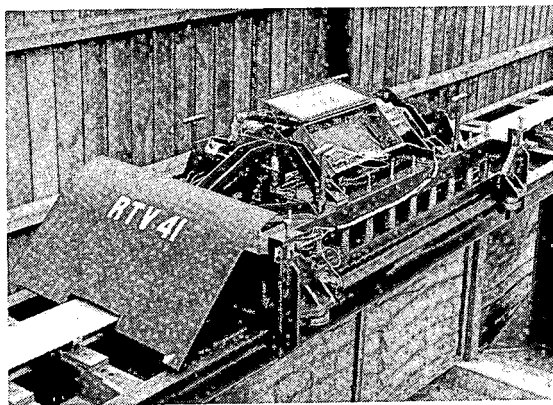


A



B

**FIGURE 1**  
**RTV31 (HOVERTRAIN CONCEPT, THL)**



A



B

FIGURE 2  
RTV41 QUARTER SCALE LIM TEST VEHICLE (THL)

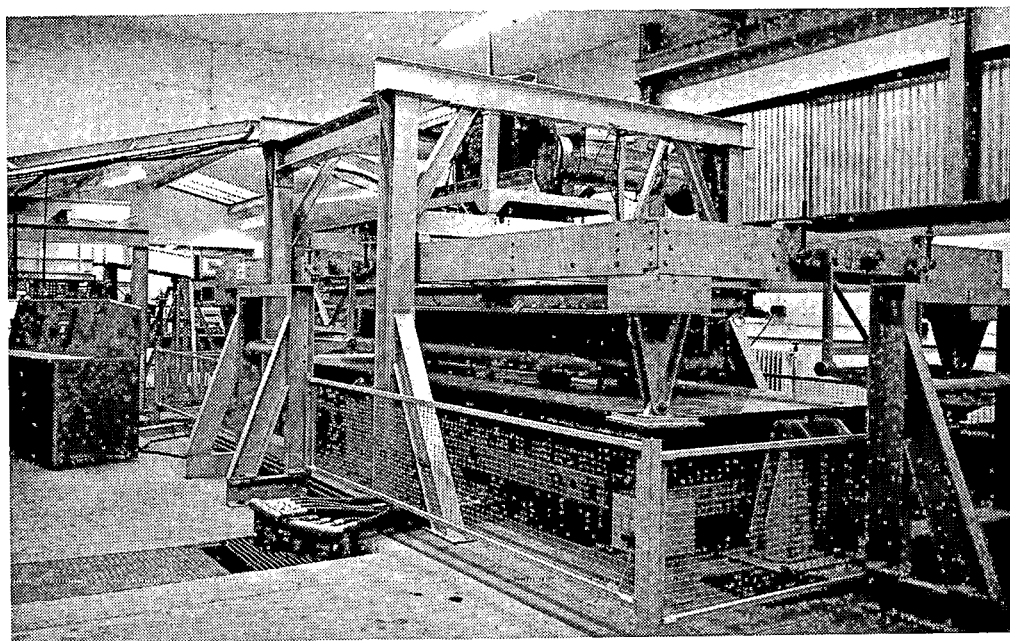


FIGURE 3  
HOVERPAD TEST STAND (THL)

### 3. Linear Motor Guidance (Figure 4)

The testing of a servo controlled guidance system for the SLIM was planned to improve the efficiency of the SLIM by maintaining a constant 2.5 cm clearance. This system was intended for use in the second phase of the test program.

This program expended approximately \$12 million in development cost between September 1967 and its termination in February 1973.

## 2.2 France

The initiation of air cushion development at Bertin and Co. began in 1957. In 1965 the Société-de l'Aérotrain was formed to develop the Aérotrain concept. The 01 experimental Aérotrain began tests in December of 1965, and reached a speed of 345 km/hr in December 1967 on a 6.7 km guideway of inverted-T design. This 10.4 m long vehicle was originally propelled with a light aircraft engine and propeller (Figure 5), then with an aircraft turbojet engine. Both propulsion systems were supplemented by solid fuel rocket boosters. The booster can be seen in Figure 5A.<sup>2</sup> All cushions were of the plenum chamber type. Air supply to the cushions was by fans driven by two 37.3 kw automotive engines.

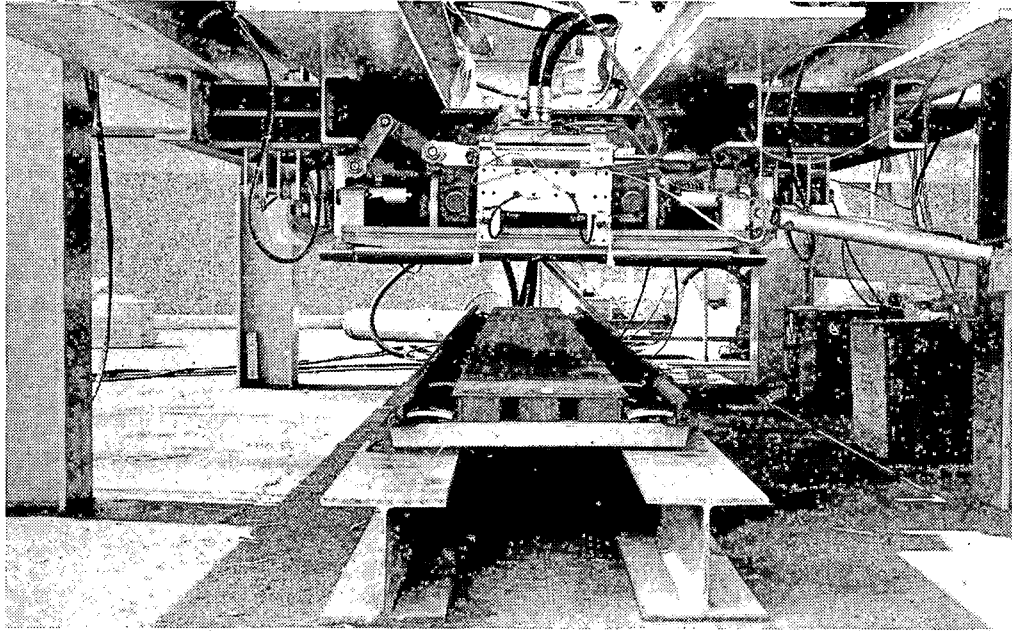
The 02 experimental Aérotrain (with a turbojet engine), shown in Figure 6, attained an average speed of 411 km/hr in January 1969. It was tested on the same guideway as the 01 Aérotrain prototype. A purely experimental vehicle with no provision for passengers, the 02 was designed primarily to test the concept of "dynamic feeding" of the air cushions.

A commercial prototype air cushion vehicle, designated the "Suburban", was tested in 1969. This 14.3 m long, 12 ton vehicle was

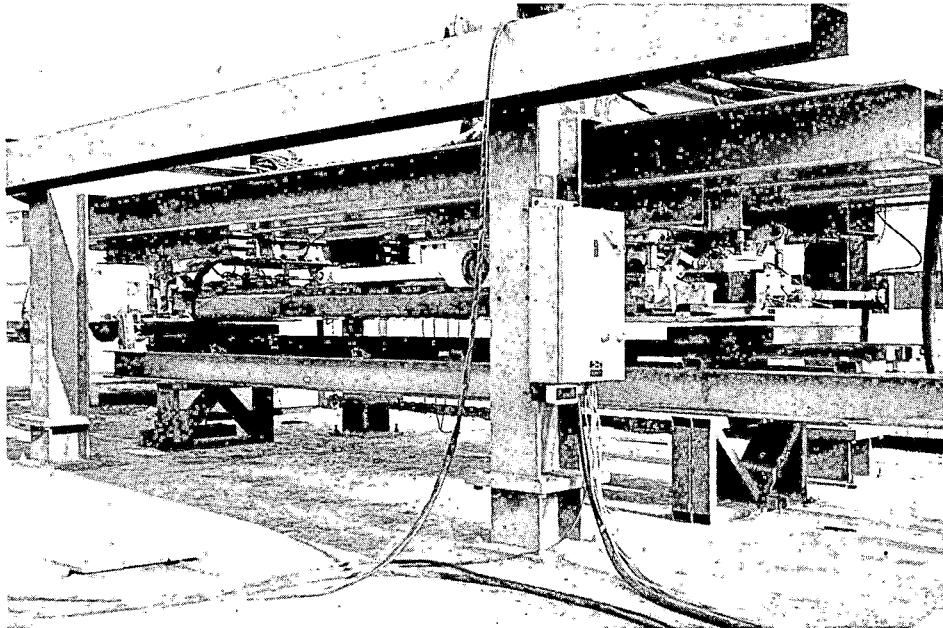
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<sup>2</sup>Photo by S<sup>té</sup> Bertin.



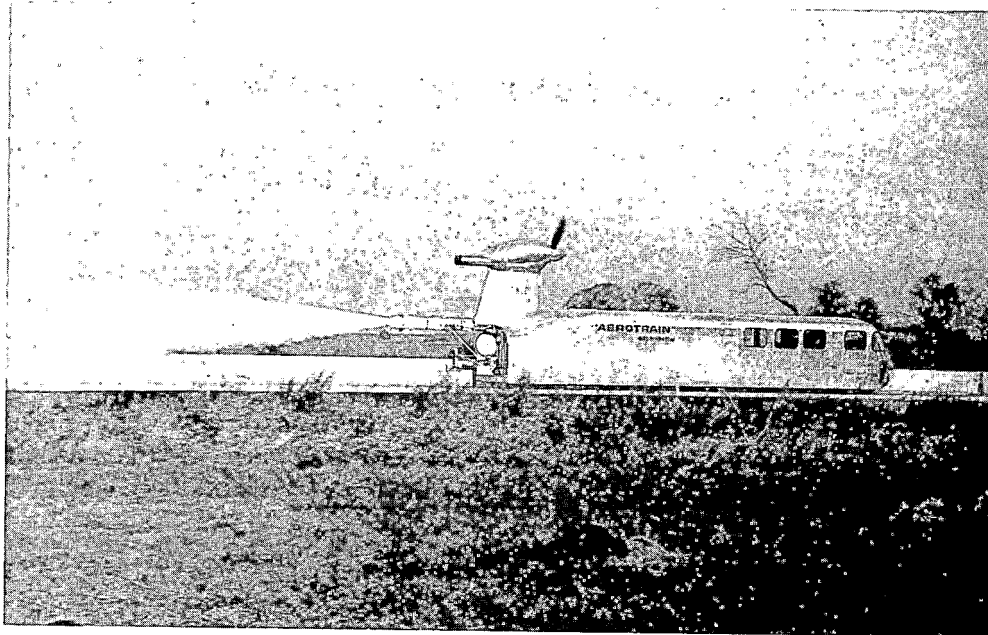


A

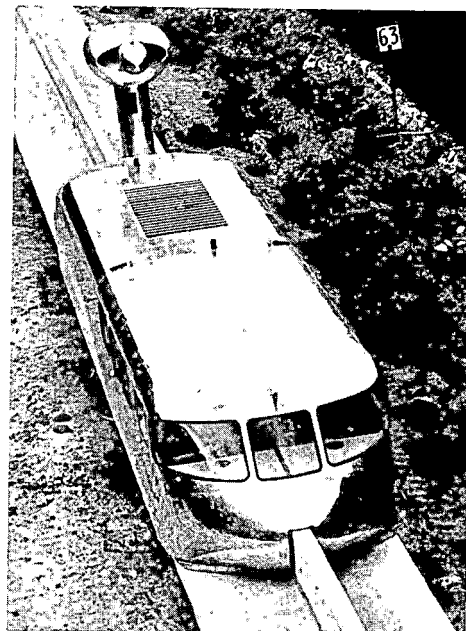


B

**FIGURE 4**  
**LINEAR MOTOR TEST STAND FOR SERVO-GUIDANCE**  
**EXPERIMENTS (THL)**

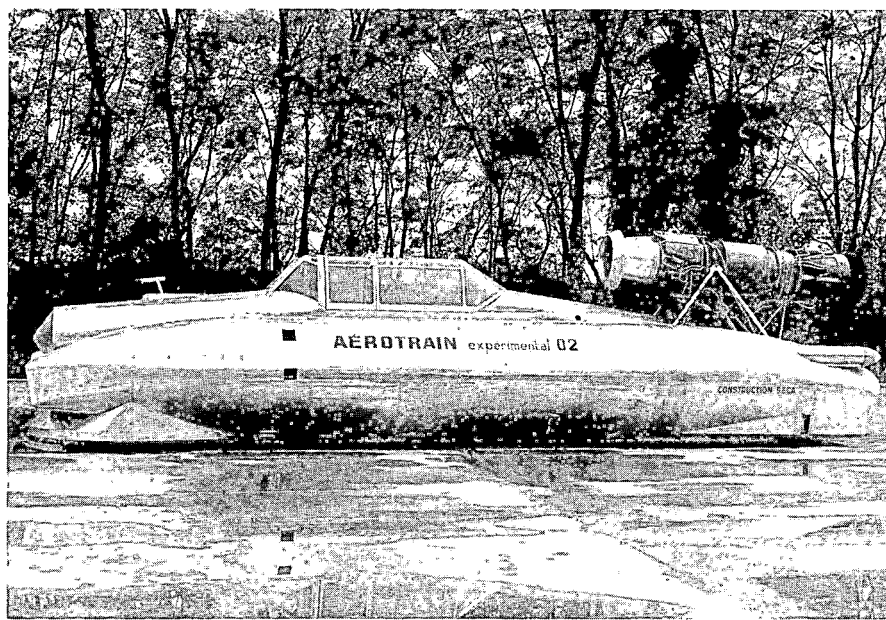


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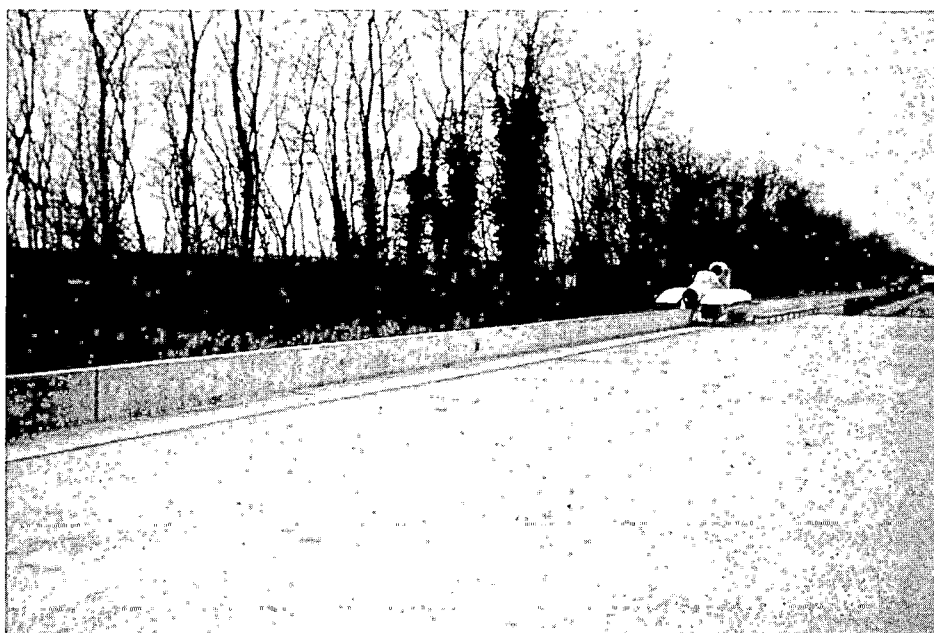


B

**FIGURE 5**  
**01 EXPERIMENTAL AEROTRAIN**



A



B

**FIGURE 6**  
**02 EXPERIMENTAL AEROTRAIN**

designed to seat 44 people with a cruising speed of 180 km/hr. Propulsion was by means of a linear induction motor. The air cushions were powered by a separate automobile engine, hence the Suburban was not an all electric vehicle.

The aerotrain program also led to the construction of another commercial prototype in 1969--an 80 passenger interurban vehicle (designated I-80), powered by a shrouded turboprop system designed for a cruising speed of 250 km/hr. The I-80 (Figure 7) was tested from September 1969 to December 1972 on a 18 km long elevated guideway of inverted-T design.

In 1973 the I-80 was equipped with a new high speed propulsion system to permit studies at higher speeds. In March 1974, this vehicle (designated the I-80 high speed Aerotrain) reached a speed of 430 km/hr.

Testing at a reduced level has continued in 1976.

### 2.3 West Germany

The company Krauss-Maffei A.G. (KM) made a comparison between two suspension candidates - one with an air cushion suspension and one with a maglev suspension. Two experimental vehicles were constructed - each with propulsion by an inverter/LIM system. Both were designed for testing on the same guideway under identical operating conditions. Figure 8 depicts the cross sections of each vehicle.

Testing of the air-cushion vehicle, designated the TR03, began in 1972. The 930 m long dual purpose guideway included a curved section with an 800 m radius of curvature. Figure 9A shows the TR03 on this guideway.

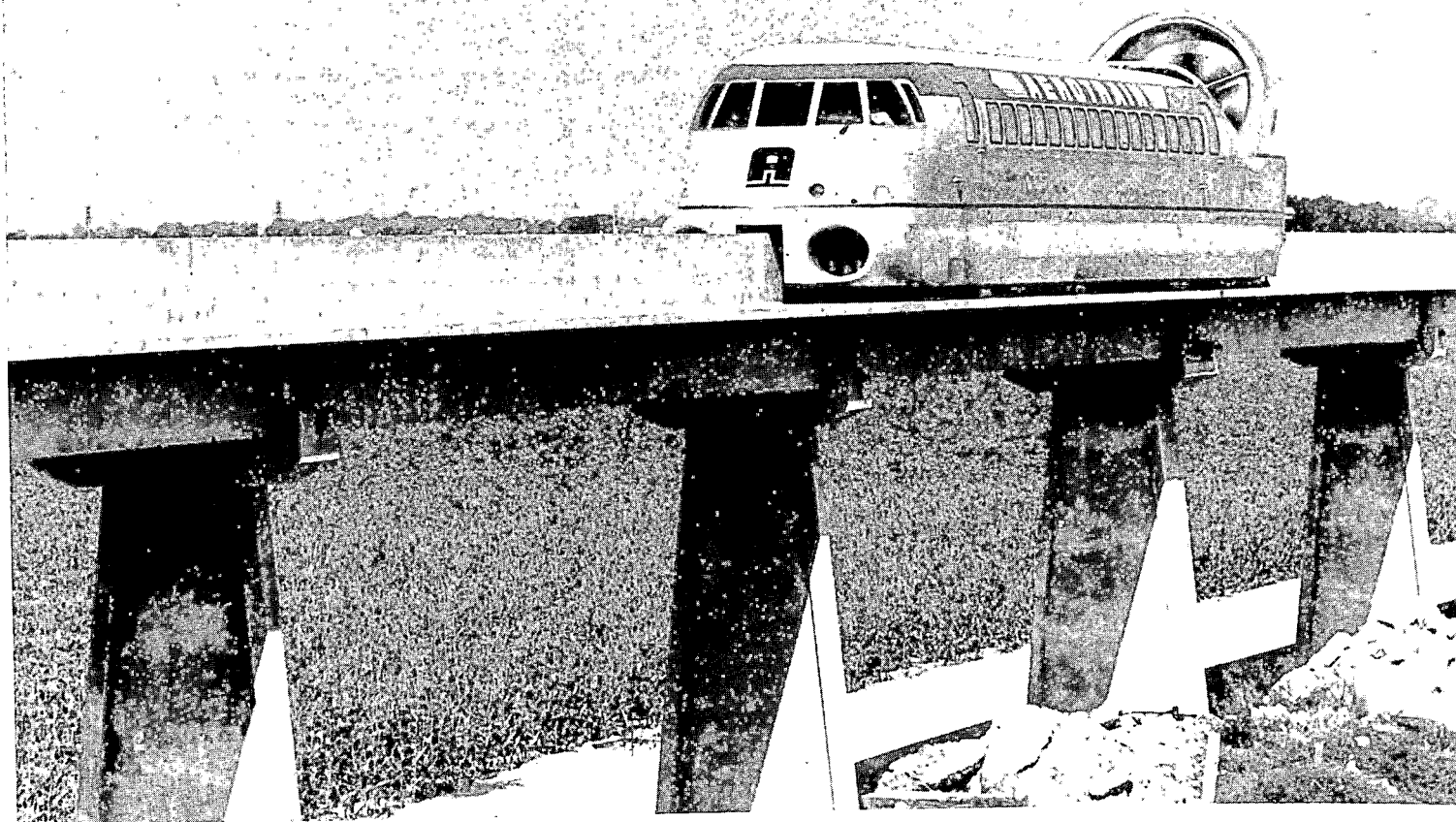
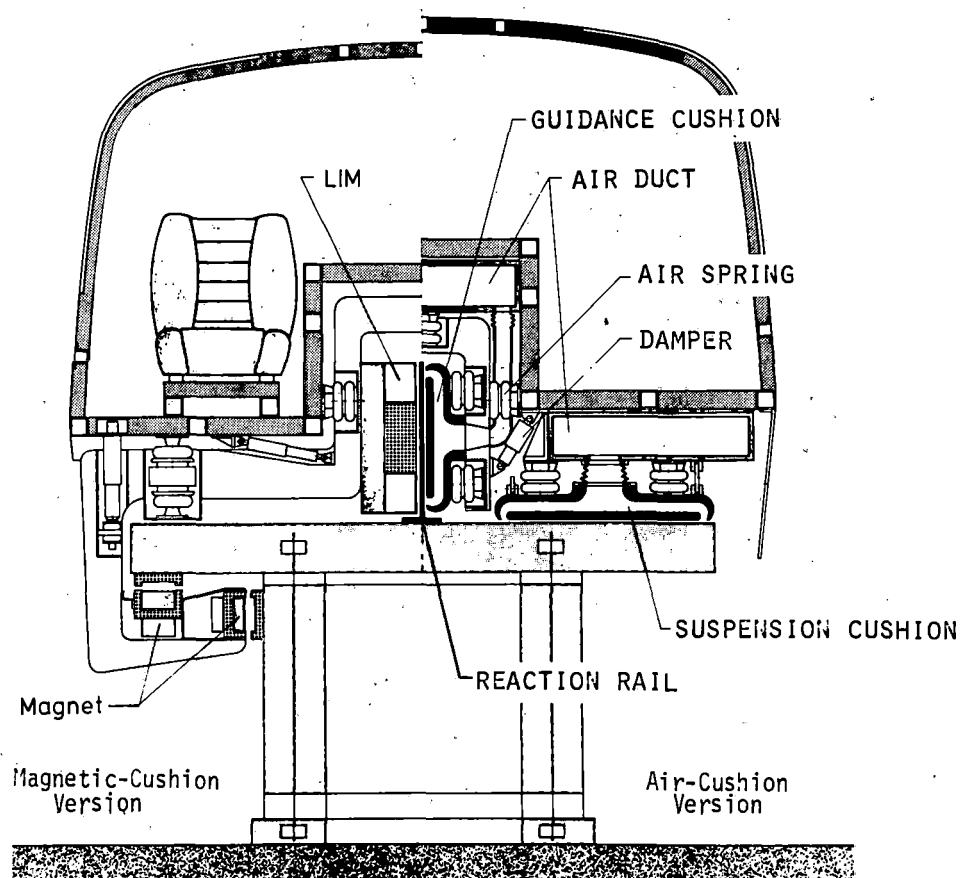
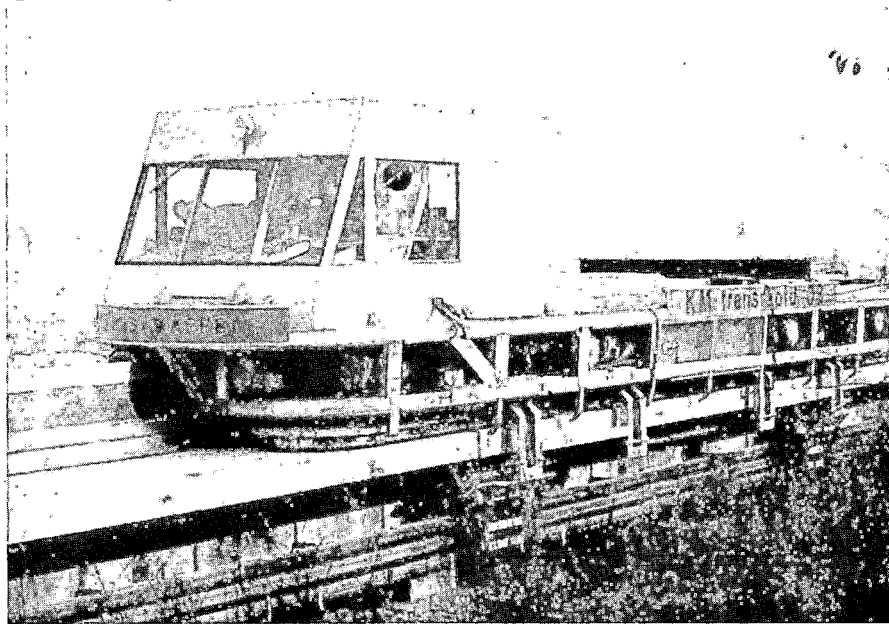


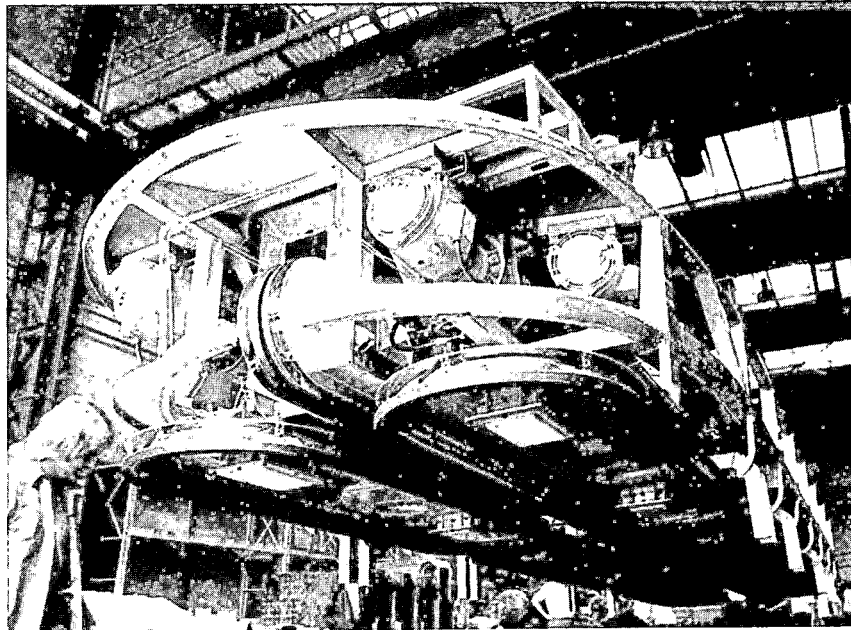
FIGURE 7  
INTERURBAN I-80 AEROTRAIN (80 PASSENGER PROTOTYPE)



**FIGURE 8**  
**COMPARISON OF TR03 (AIR CUSHION) AND TR02**  
**(MAGLEV) CONFIGURATIONS**



A



B

**FIGURE 9**  
**TR03 (AIR CUSHION) TEST VEHICLE (KM)**

This 11.7 m long vehicle weighed 9.6 tons and was designed for a maximum speed of 140 km/hr. Suspension and guidance were by plenum type air cushions (six cushions for lift, eight for guidance). Each air cushion was driven by a separate air supply consisting of an axial fan driven by an electric motor. Figure 9B shows the chassis from below.

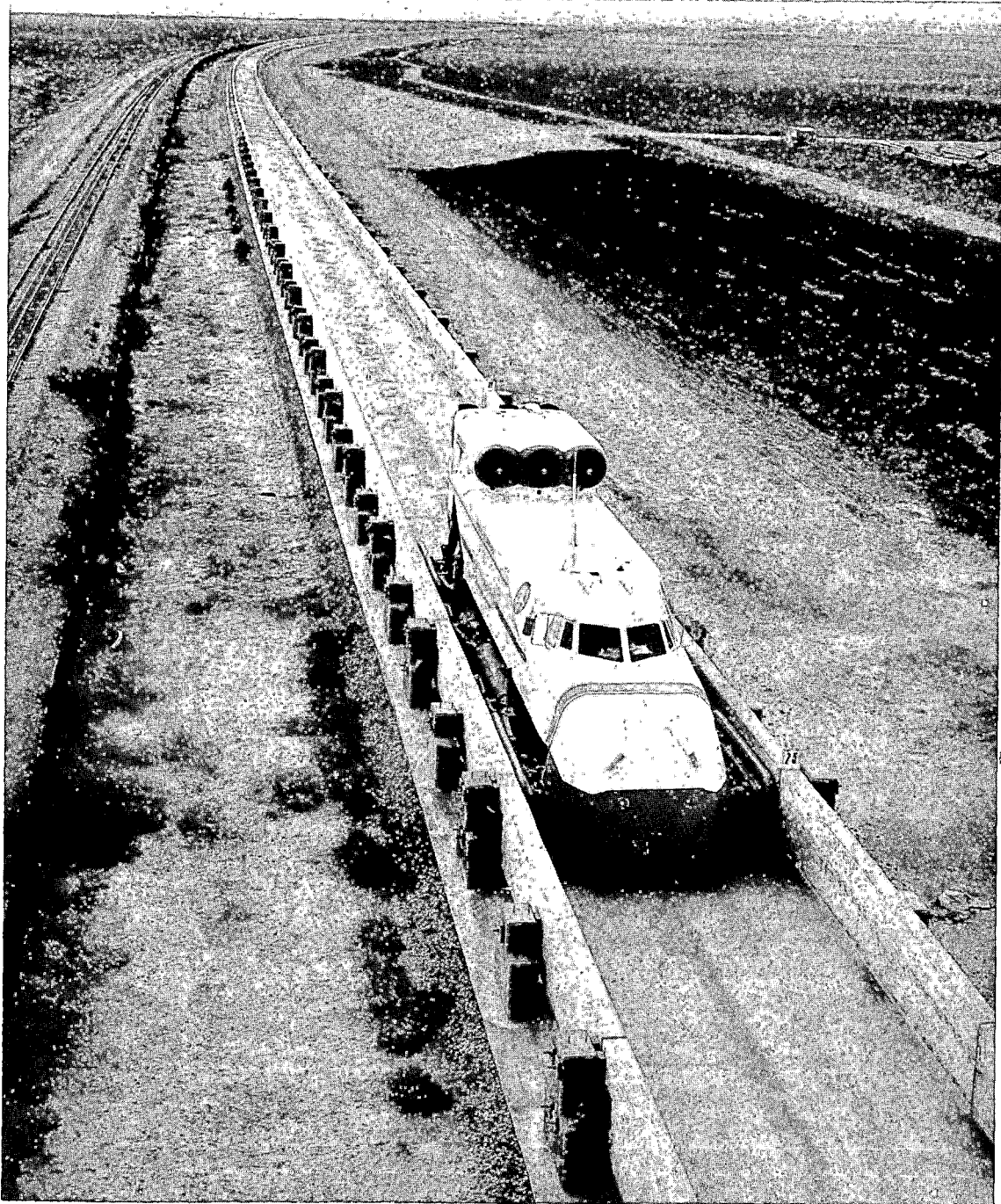
Further development of the air cushion technology was stopped when the results of the comparison led to the selection of a maglev suspension.

#### 2.4 United States

In 1970, the Federal Railroad Administration (FRA) of the U.S. Department of Transportation awarded contracts to Grumman Aerospace Corporation for the engineering design and construction of a 480 km/hr test vehicle utilizing air cushion suspension. Garrett Corporation was chosen to provide a LIM propulsion system and its wayside power distribution and collection systems. This air cushion vehicle, designated the TLRV, was 15.6 m long and weighed 15.4 tons without the LIM system. The TLRV, shown in Figure 10, operated in a channel shaped guideway using four air cushions for levitation and four for guidance. All the cushions were of the peripheral jet type. The TLRV had a secondary suspension between the body and chassis as well as between the chassis and the air cushions. Three fully shrouded, high bypass ratio JT15D-1 turbofan engines, mounted aft, were to be used in the aeropropulsion mode to a speed of 200 km/hr. The LIM system was planned to consist of two identical LIM/inverter systems, as shown in Figure 11.

Tests of the vehicle in an aeropropulsion mode began in May of 1973. By the end of aeropropelled testing in December 1973, speeds to 147 km/hr had been attained. Although initial plans were for a 35 km oval shaped test track, only 4.8 km were completed, limiting the maximum test speed.





**FIGURE 10**  
**TLRV (TRACKED LEVITATED RESEARCH VEHICLE)**

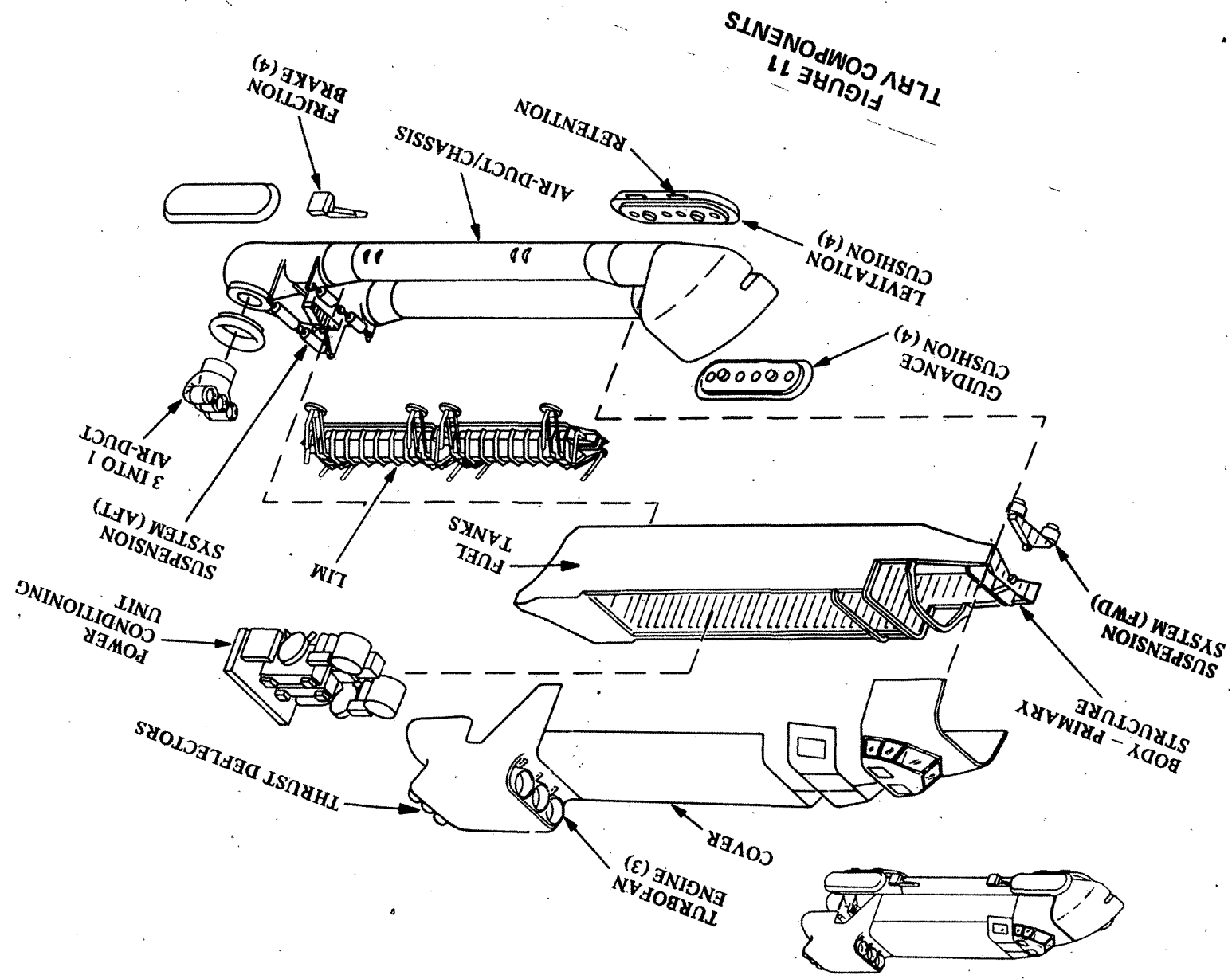


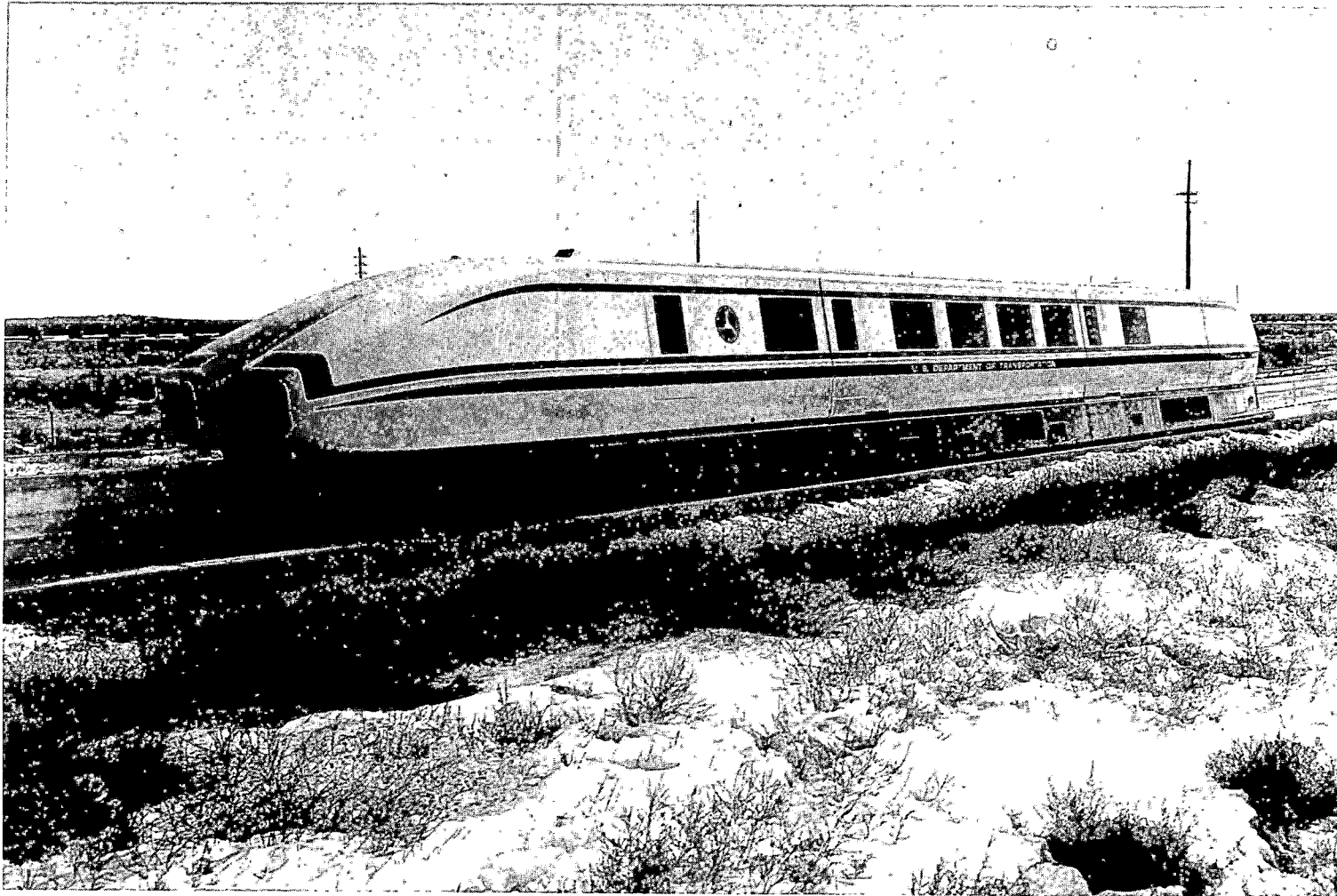
FIGURE 11  
TLRV COMPONENTS

Installation of the first half of the LIM propulsion system (one LIM, one PCU) was completed in 1975. The TLRV (with a LIM) was tested only at low speeds (about 70 km/hr) in March 1976, limited by the reaction rail length of 500 m existing at that time. The second LIM was never fabricated. This test program was terminated in 1976.

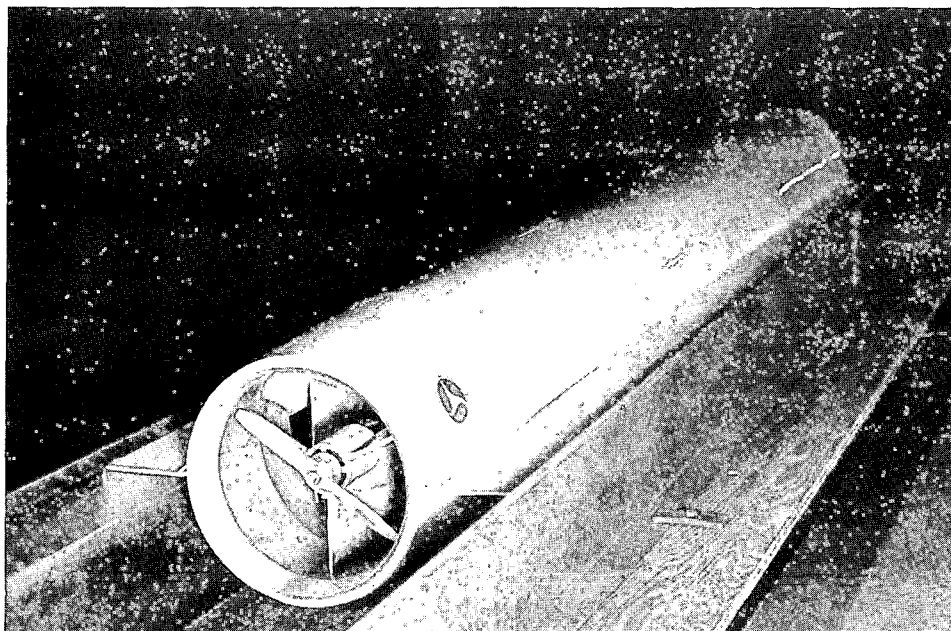
In 1973 a full scale prototype of an all electric air cushion vehicle, the PTACV, was built for the DOT by Rohr Industries, Inc. to demonstrate the existing state of the art of air cushion and LIM technology. The PTACV, designed to carry 60 passengers at 240 km/hr, relied heavily on the French Aerotrain cushion design and LIM applications. This vehicle, 28.6 m long, with a gross weight of 29.6 tons is shown in Figure 12. The guideway is of the inverted-T design. Although 17.1 km of test track were originally planned, only 9.2 km were completed before the termination of the test program in 1976. The PTACV was successfully tested up to speeds of 232 km/hr in 1976.

The suspension air cushions for this vehicle feature both close-running seals and a pneumatic secondary suspension, integrating both the primary and secondary suspension into the air cushion. Propulsion was by means of a fixed frequency (60 Hz) double sided linear induction motor utilizing a vertical reaction rail. This rail also served as the guidance surface for the vehicle's air cushions. The LIM is suspended from two linear bearings mounted laterally in the vehicle and is guided on the reaction rail by pinch wheels at each end of the motor.

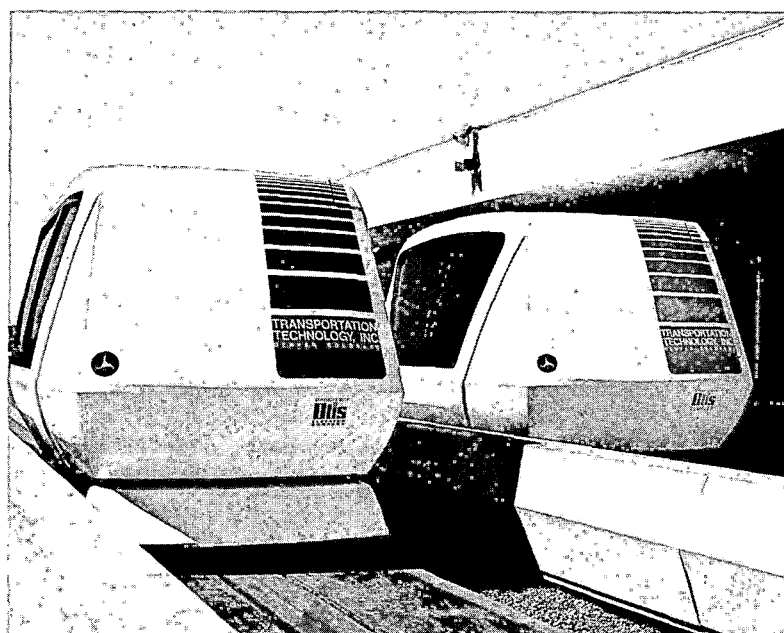
In addition to the conventional air cushion (plenum and peripheral jet) research, small scale laboratory experiments are being carried out on the ram air cushion at Princeton University. Figure 13 shows the small (1.8 m long) model tested at Princeton in 1974. Experiments will continue through 1977.



**FIGURE 12**  
**PTACV (60 PASSENGER, ALL ELECTRIC, PROTOTYPE**  
**TRACKED AIR CUSHION VEHICLE)**



**FIGURE 13**  
**SMALL SCALE RAM AIR CUSHION MODEL**



**FIGURE 14**  
**LOW SPEED PRT PROTOTYPE (TTI)**

In addition to the higher speed research mentioned above, work has been pursued on lower speed vehicles. Figure 14<sup>3</sup> shows a low speed (50 km/hr) vehicle constructed by Transportation Technology, Inc. (TTI) for TRANSP0 '72 at Dulles Airport near Washington, D.C. Propulsion is by means of a linear induction motor.

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<sup>3</sup>Cover Photo, Materially Speaking, Vol. 20, June 1973.

### 3.0 ATTRACTION MAGLEV

The development of attraction maglev has been most advanced in West Germany, followed by Japan and the United States. These efforts are discussed further in this section.

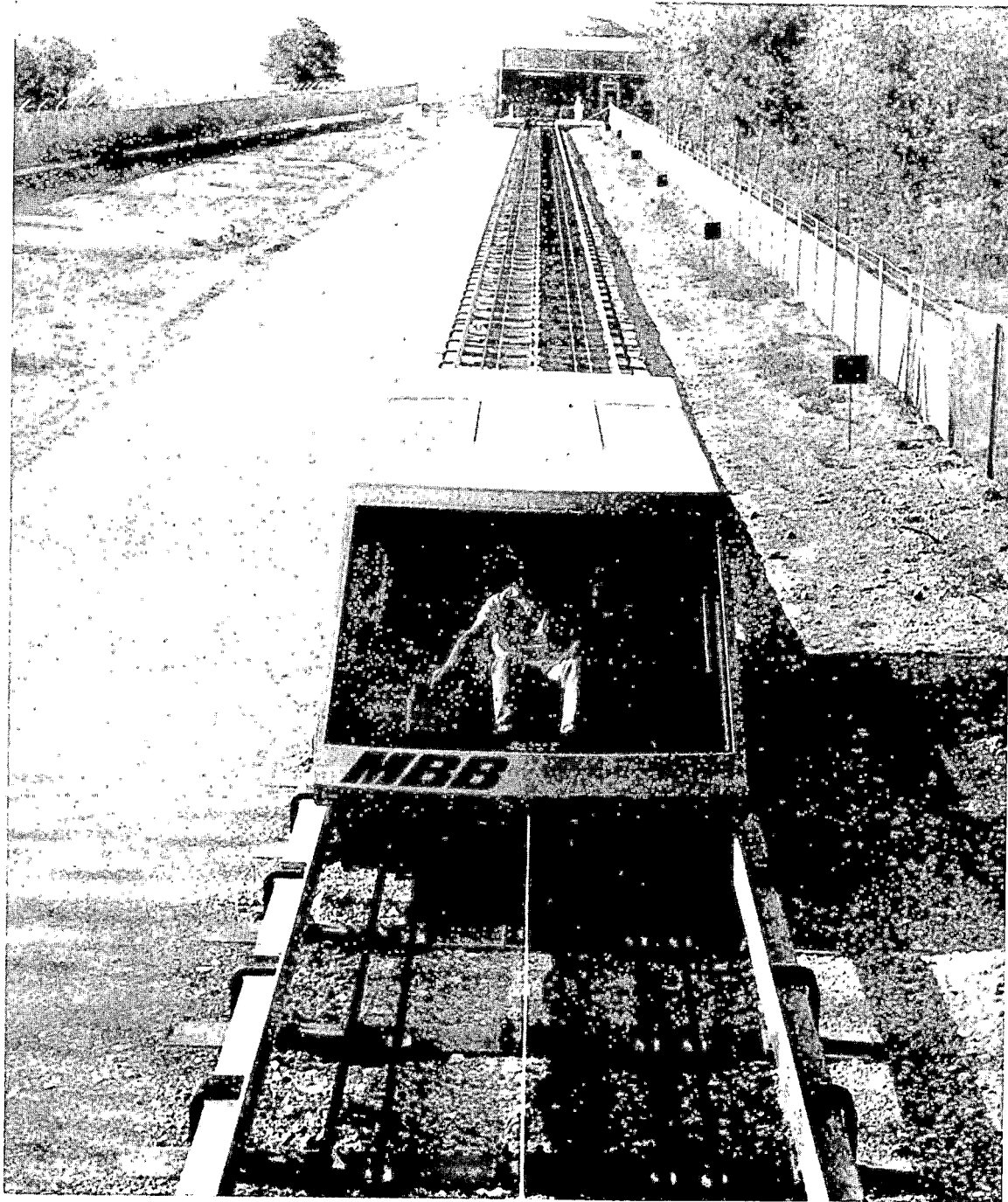
Attraction maglev has also received attention in Canada, at the National Research Council in Ottawa and the University of Toronto, as well as in France, in the USSR, and in England.

#### 3.1 Germany

In May 1971 the company of Messerschmitt-Bölkow-Blohm (MBB) demonstrated a basic vehicle to the public. This vehicle, shown in Figure 15, was levitated by 8 electromagnets and laterally guided by 4 electromagnets. Propulsion was by a linear induction motor (double sided) using a vertical reaction rail. The design speed of 90 km/hr was achieved on the 660 m straight test track.

In 1972 operation of a second test vehicle started. This 3.6 m long test vehicle, weighing 1.3 tons, consisted of a platform supported and guided by wheels and accelerated by a hot water rocket. This magnet test vehicle was used to carry magnets for testing at speeds up to 225 km/hr on the 660 m test track.

In October 1971, Krauss-Maffei demonstrated to the public an 11-ton magnetically levitated experimental vehicle, designated the TR02, shown in Figure 16. This 11.7 m long vehicle was propelled by a fixed frequency (50 Hz) double sided linear induction motor. It was tested at its design speed of 164 km/hr. This vehicle was levitated and guided along U-shaped rails by 16 electromagnets. These magnets were arranged in the combined levitation/guidance configuration (whereby a pair of longitudinally adjacent magnets are staggered about the rail centerline so as to achieve both levitation and guidance forces).



**FIGURE 15**  
**EXPERIMENTAL VEHICLE (MBB)**



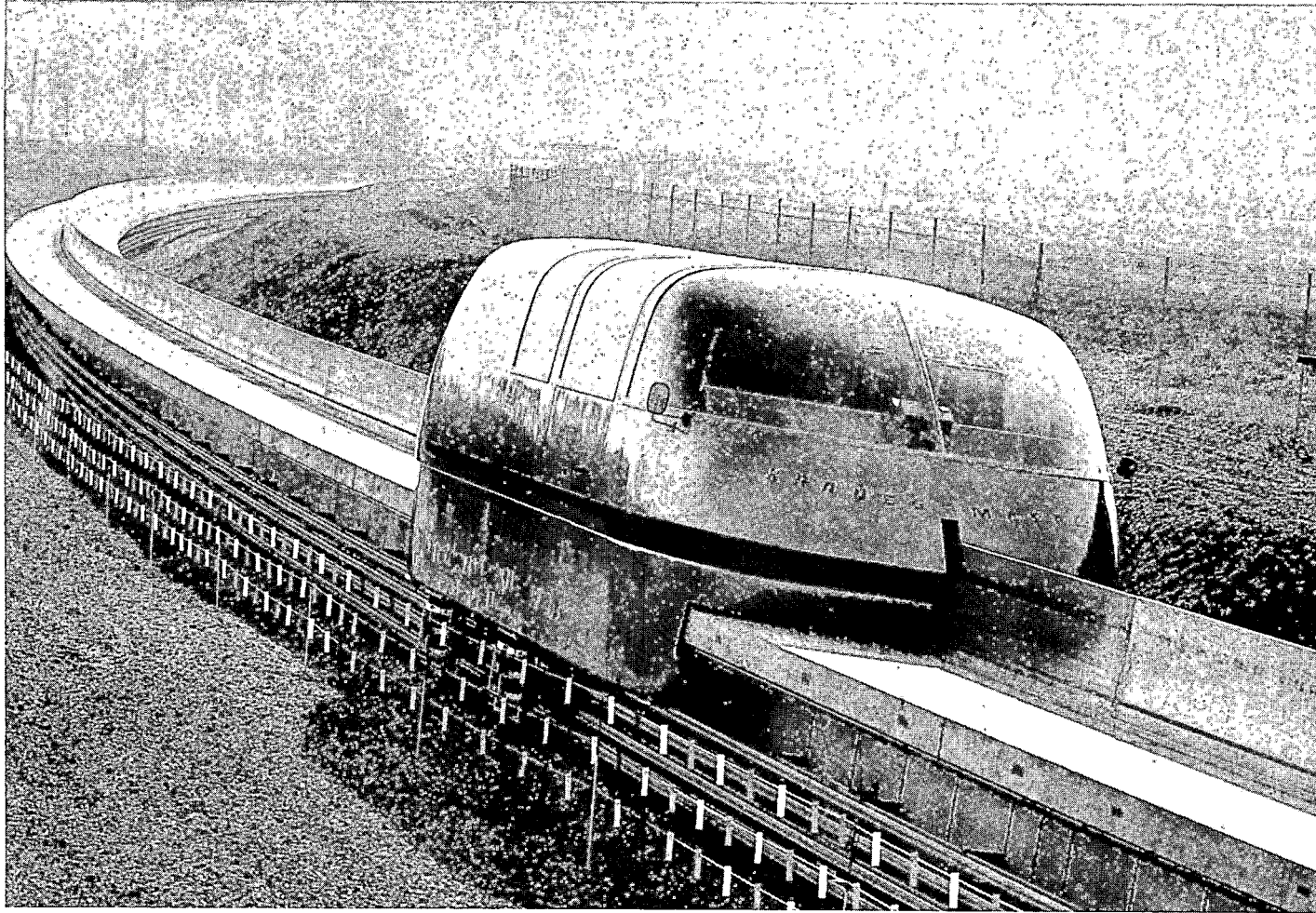


FIGURE 16  
TR02 (TRANSRAPID CONCEPT-KM)

Figure 17 shows the TR04 constructed by Krauss-Maffei. This vehicle is the largest passenger-carrying magnetically levitated and LIM propelled experimental vehicle to date. The vehicle is 15.0 m long and weighs 16.5 tons. Suspension and guidance are by electromagnets arranged in the combined levitation/guidance configuration. Propulsion is by a double sided linear induction motor. The LIM reaction rail is mounted horizontally on the guideway. The vehicle was designed for a maximum test speed of 250 km/hr, but has not been tested at that speed to date.

The 2.4 km TR04 test track contains curves with radii of curvature from 800 m to 3,100 m and a maximum grade of  $\pm 11^\circ$ . This test installation was intended to allow testing of various system components under realistic conditions as a basis for developing future large scale test facilities.

A test facility, designated LHP, is shown in Figure 18. It consists of an unmanned, magnetically levitated and guided test vehicle and a 1.3 km test track. The vehicle, designated "KOMET", contains a mounting rack for components to be carried over a test bed. The KOMET is 8.5 m long and weighs 8.8 tons (empty). Levitation is accomplished by 10 electromagnets (5 on each side), guidance is obtained with 4 magnets, one at each corner. The magnets are used in a separate levitation/guidance configuration. The test bed, shown in Figure 19, is 300 m long and lies along the track centerline.

The component carrier KOMET is accelerated by a thrust sled equipped with up to six hot-water rockets in order to achieve test speeds up to 400 km/hr. After acceleration, the KOMET separates from the thrust sled and coasts through the test section until braking is initiated. This facility has been in use since 1974.

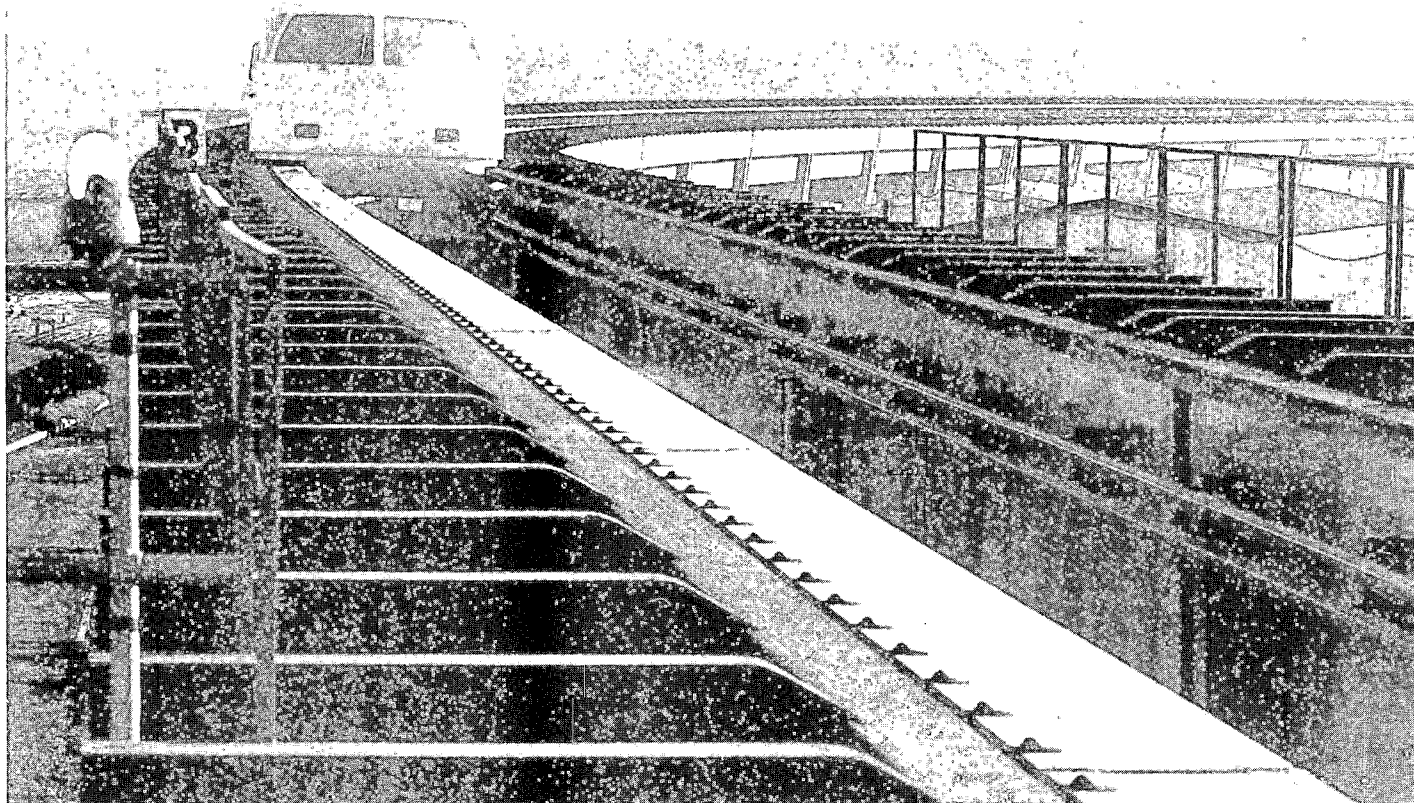
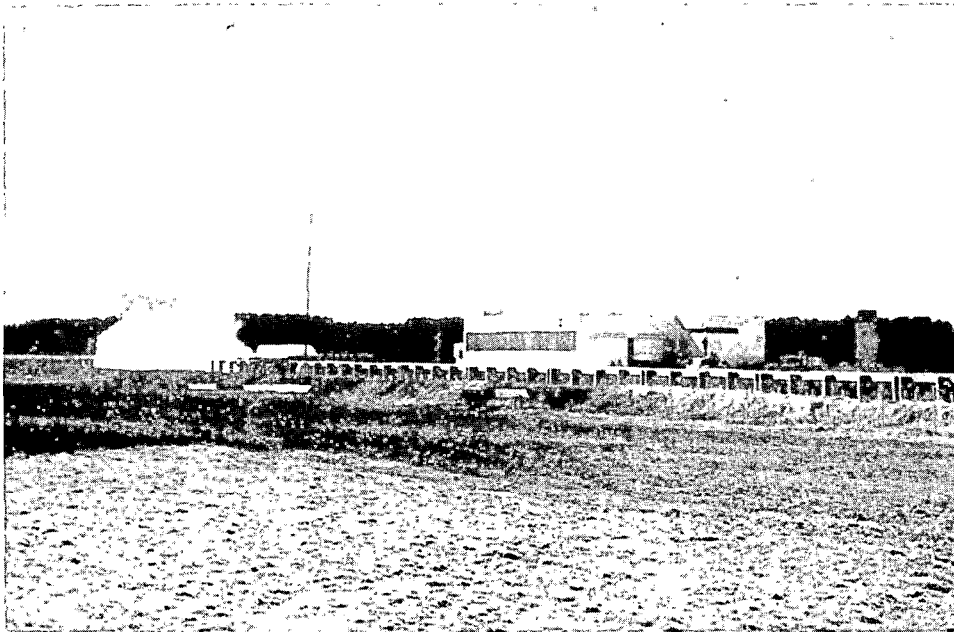
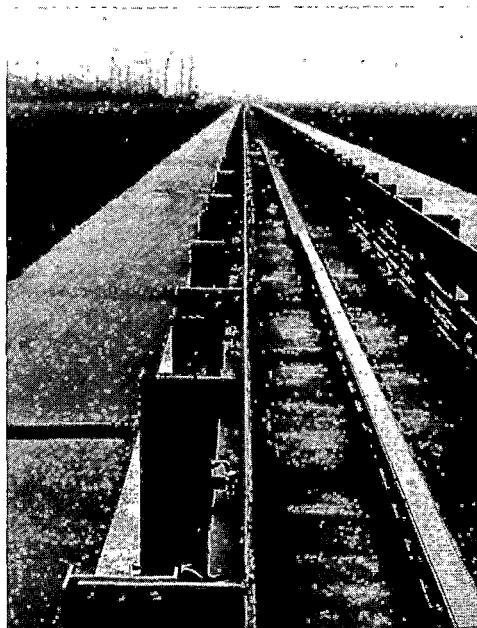


FIGURE 17  
TR04 (TRANSRAPID CONCEPT-KM)



**FIGURE 18**  
**LHP TEST FACILITY (MBB)**



**FIGURE 19**  
**COMPONENT TEST BED AT LHP FACILITY**

In support of these activities several static as well as dynamic test stands and rotating wheel facilities have been constructed. Figure 20 shows a DLIM test stand. The DLIM shown is 2.5 m long. Figure 21 shows a dynamic test stand for electromagnets.

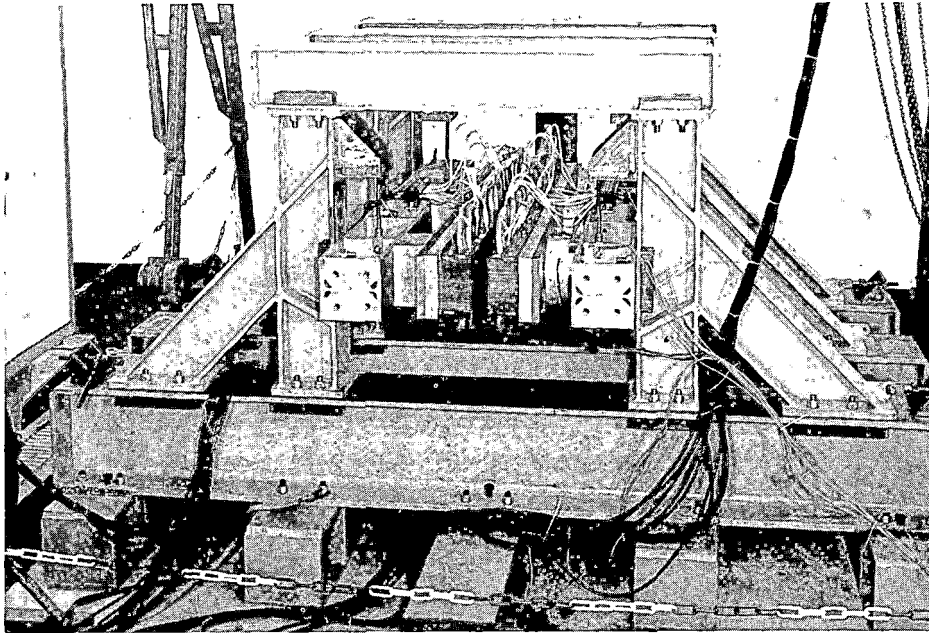
Figure 22 shows the TU02 and its test track constructed by Krauss-Maffei for its Transurban program. This 12 passenger prototype was a part of the program for the development of a low speed (80-120 km/hr) magnetically levitated/LIM propelled vehicle. The U-shaped track, shown during its construction in Figure 22B, is designed for the combined levitation/guidance magnet configuration. Testing commenced in 1973.

The efforts of Krauss-Maffei and MBB were coordinated in early 1974 by the formation of TRANSRAPID-EMS, a joint concern for the study of attraction maglev systems.

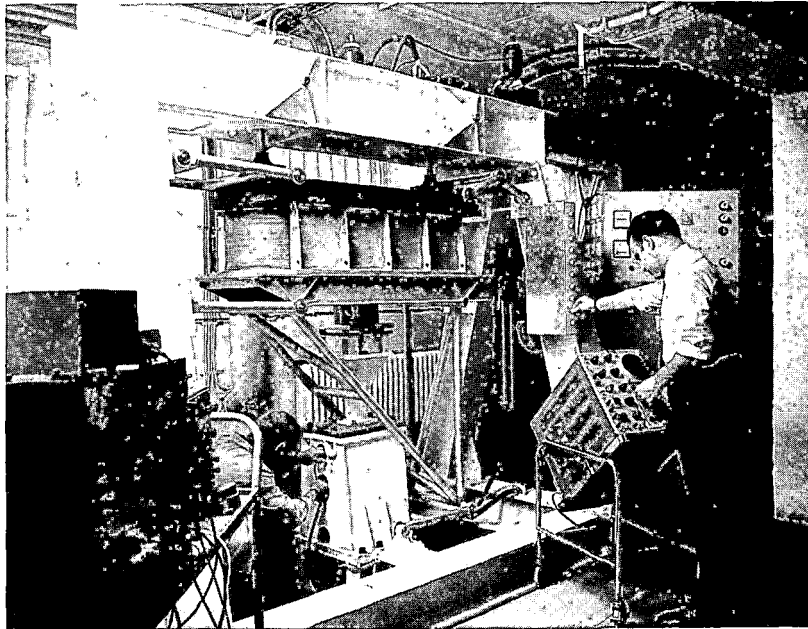
### 3.2 Japan

A project for the development of a Low Environmental Pollution Railway has been undertaken by the Ministry of Transport since 1974. This project is directed toward developing a low speed (120 km/hr) attraction maglev system. The program is being carried out by Japanese industrial firms under the direction of Universities and the Japanese National Railways (JNR).

The EML-50 (Figure 23) is a 2.8 m long, 1.8 ton test vehicle utilizing separate electromagnets for lift and guidance (four for lift, four for guidance). Propulsion is by means of a fixed frequency (50 Hz) single sided linear induction motor. Thrust control is accomplished by using switches to change the LIM winding connection. This vehicle, which is primarily intended to test control system schemes for the suspension system, has been tested at speeds up to its maximum of 40 km/hr on a 165 m straight and level track.



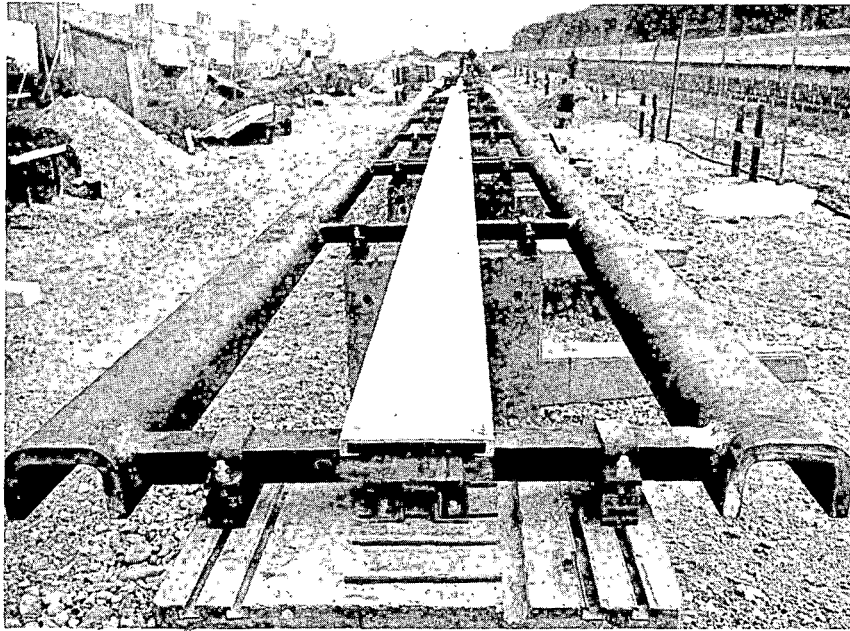
**FIGURE 20**  
**LIM TEST STAND (MBB)**



**FIGURE 21**  
**DYNAMIC MAGNET TEST STAND (MBB)**



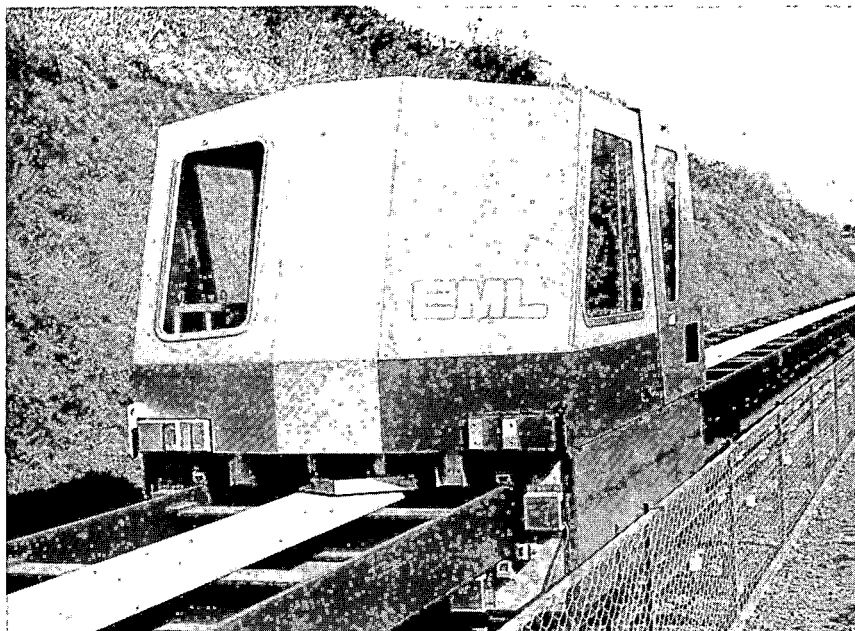
A



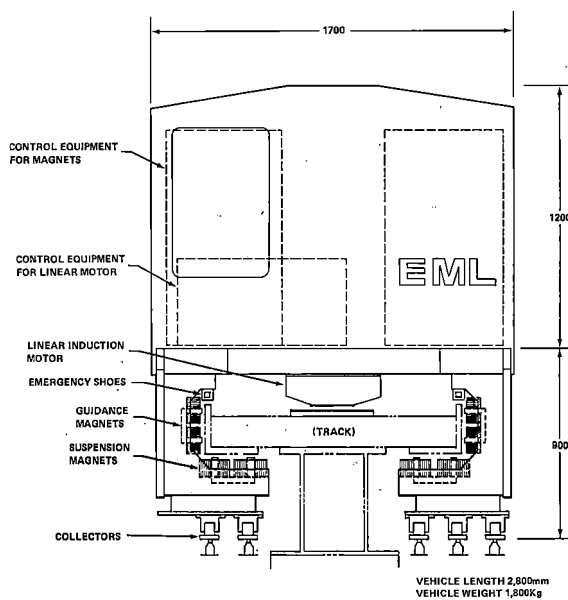
B

FIGURE 22  
TU02 (TRANSURBAN CONCEPT—KM)





A



B

**FIGURE 23**  
**EML-50 (JNR)**



For higher speed applications, Japan Air Lines (JAL) has been developing a 300 km/hr attraction maglev system for rapid airport to downtown transportation.

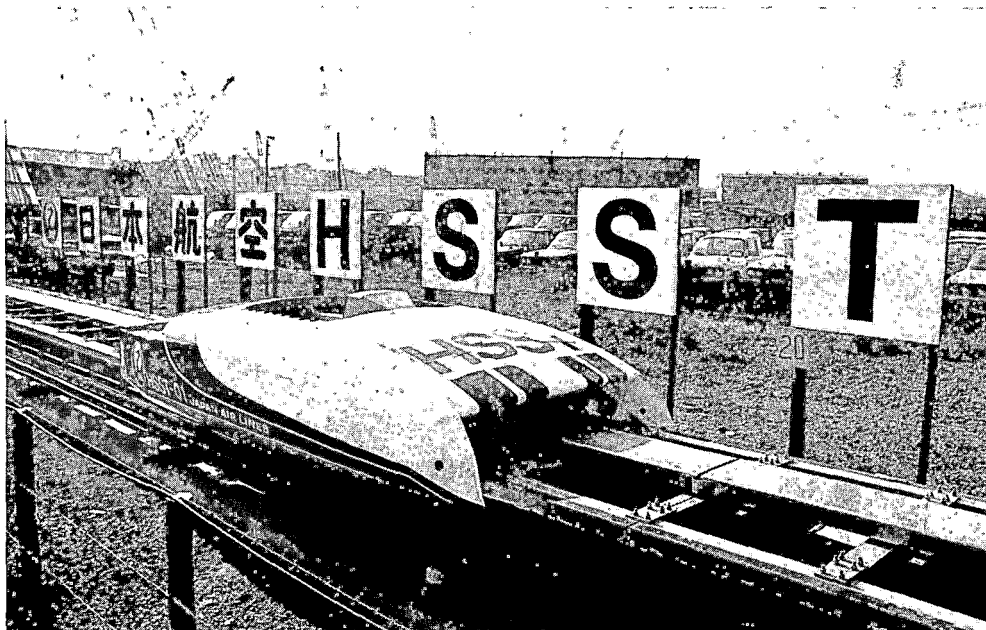
Work on a High Speed Surface Transport (HSST) system began at JAL in 1971. JAL's HSST-01 experimental vehicle, shown in Figure 24, was designed in 1973 and is now undergoing tests at speeds up to 35 km/hr. The speed is limited by the 200 m length of track. The vehicle is 4 m long, weighs 1.0 ton, and is equipped with two seats. Suspension is accomplished by eight electromagnets (4 on each side) arranged in a combined levitation/guidance configuration for a U-shaped track. Propulsion is by a single sided linear induction motor.

### 3.3 United States

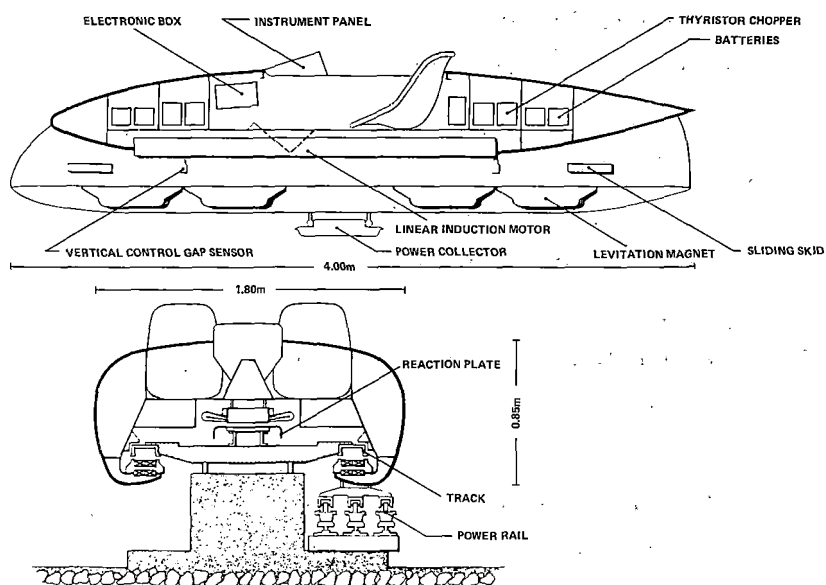
Experiments on high speed attraction maglev systems have been on a small scale. Dynamic test stands such as those used most recently (1975) at the Massachusetts Institute of Technology (Figure 25), as well as those used in 1972 at the Ford Motor Company (Figure 26), and in 1973 at MITRE/METREK (Figure 27), are typical of the scale of the experimental work concerning magnet control systems and magnet design. Analytical work, of course, has complemented the experiments.

All these experiments were for heave mode motion only. The Ford work was the largest in size, using a 45 kg magnet mounted on linear bearings. The MITRE/METREK experiment tested a small (2.2 kg) magnet using a constant force spring load to simulate a soft secondary suspension. Both the MIT and FORD experiments used a rigidly affixed weight to simulate a vehicle mass.

Rotating wheel experiments, used to ascertain the effects of eddy currents in the track, were conducted at Ford Motor Co. on a small (30.5 cm diameter) wheel in 1972 and on a larger (1.5 m diameter) wheel in 1974.

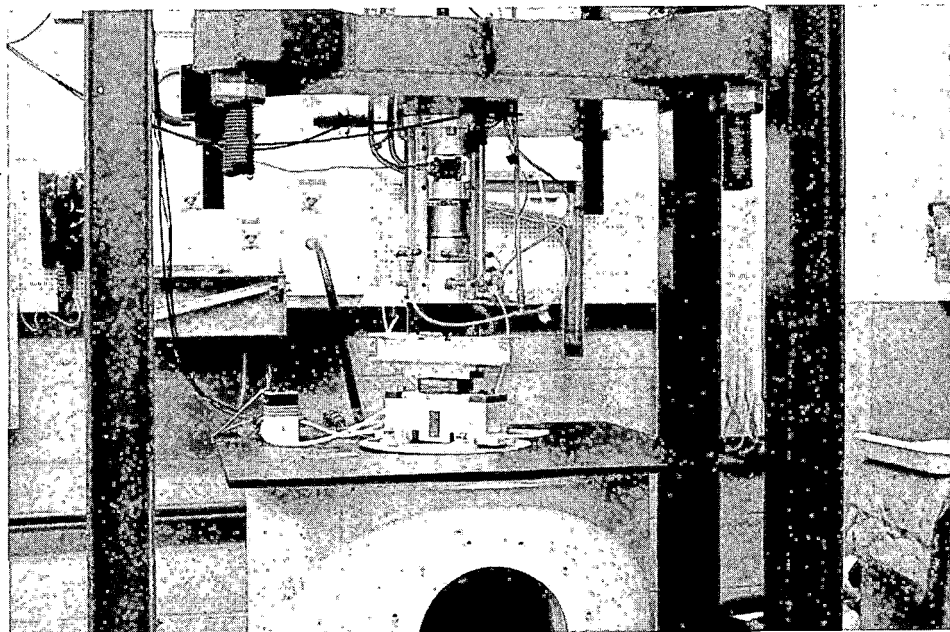


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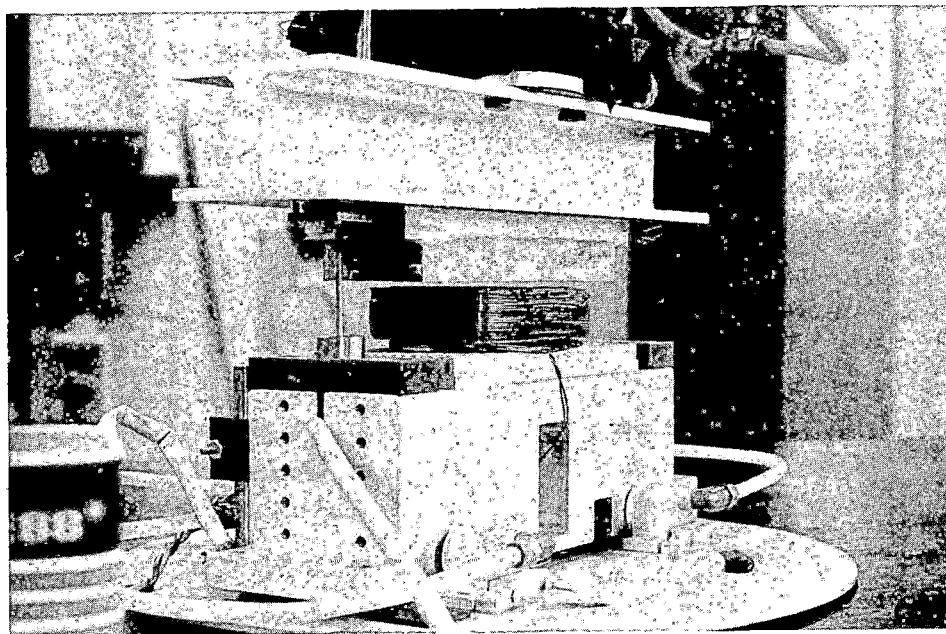


B

**FIGURE 24**  
**HSST-01 (JAL)**



A



B

FIGURE 25  
DYNAMIC MAGNET TEST STAND (MIT)

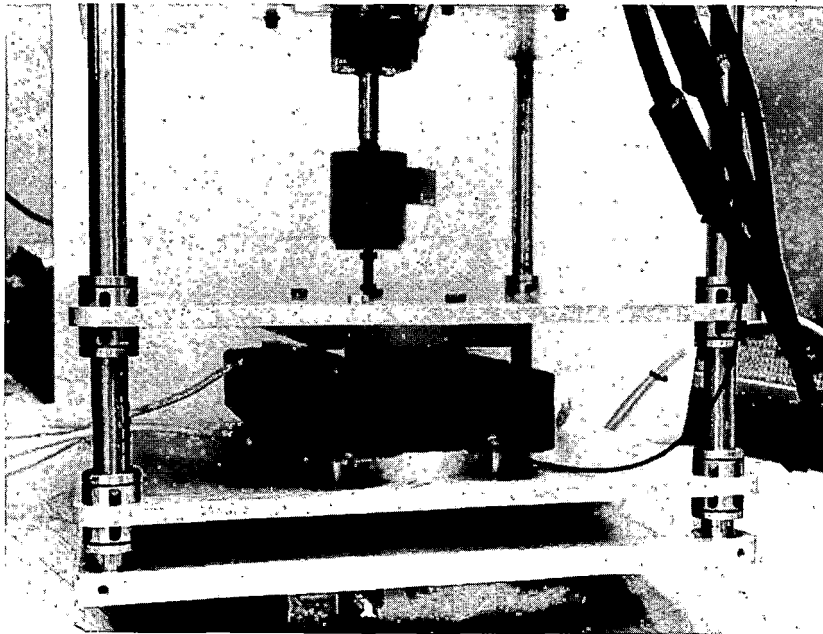


FIGURE 26  
DYNAMIC MAGNET TEST STAND (FORD)

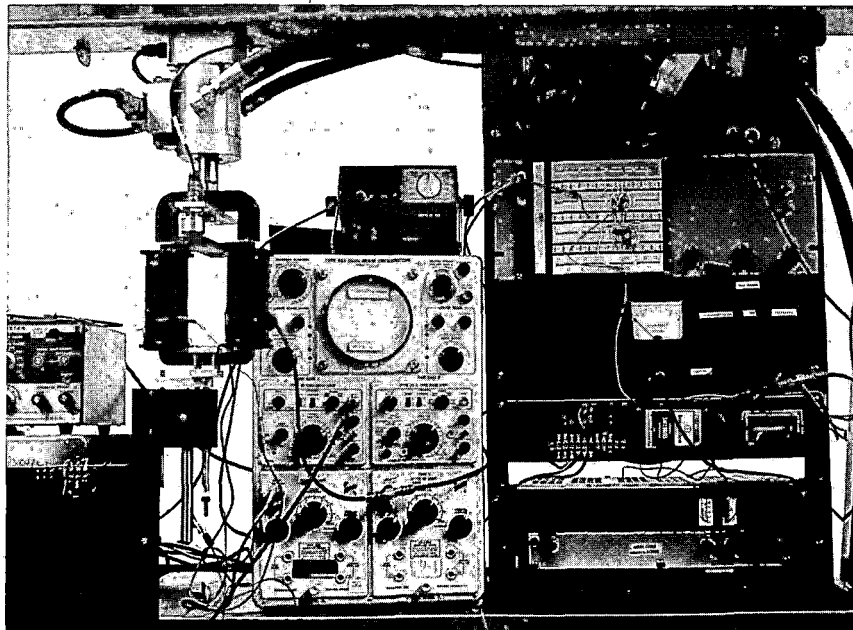
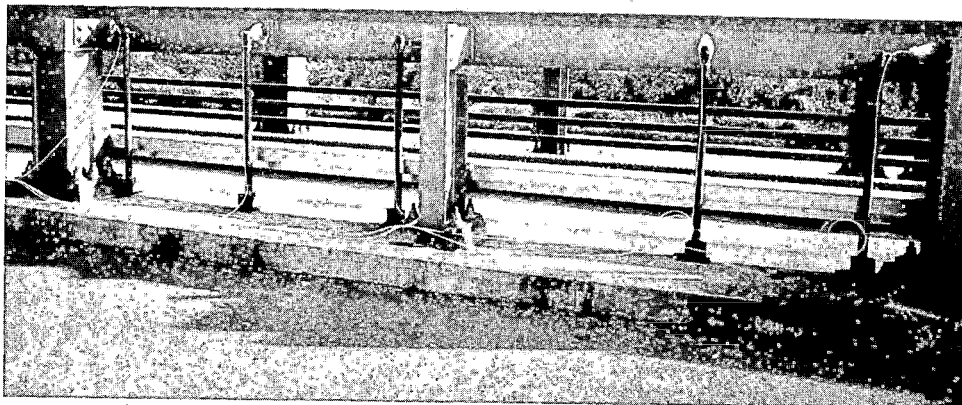


FIGURE 27  
DYNAMIC MAGNET TEST STAND (MITRE/METREK)

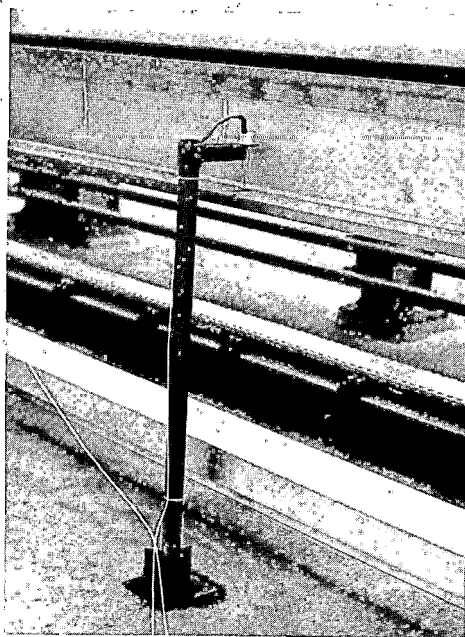
In 1976, cooperation between the U.S. DOT and the West German government led to a joint experiment on flexible guideways. In this experiment, carried out in October 1976, the guideway for the KOMET at the LHP facility in Germany was made more flexible by loosening the bolts between the piers and rail at some of the piers throughout a 48 m test section. The LHP facility was shown in Figure 18. An instrumented section of the modified guideway used for these tests is shown in Figure 28.

A U.S. DOT program was initiated in 1976 in which a test program is to be conducted at the Canadian Institute for Guided Ground Transport (CIGGT) in Canada. The CIGGT facility is discussed in Section 4.1. The purpose of this program is to study the feasibility of using a single sided linear induction motor (SLIM) as a combined suspension/propulsion machine for vehicle speeds up to 500 km/hr. In this concept, the inherent attraction forces in the SLIM will be utilized to provide levitation, lateral guidance and propulsion.

ROHR Corporation has focused on providing suspension as well as propulsion from a SLIM. Designated ROMAG, two SLIMs, one along each side of the vehicle, are controlled to provide the suspension and propulsion forces. Rohr has demonstrated two low speed vehicles, one at grade and one on an elevated guideway on a short test track. These vehicles are shown in Figure 29. The vehicle at grade level attained a speed of 56 km/hr in March 1971 on a 381 m long guideway. The elevated vehicle attained a speed of 48 km/hr in June 1973 on a 457 m long guideway.



A



B

**FIGURE 28**  
**LHP GUIDEWAY INSTRUMENTATION (MBB)**



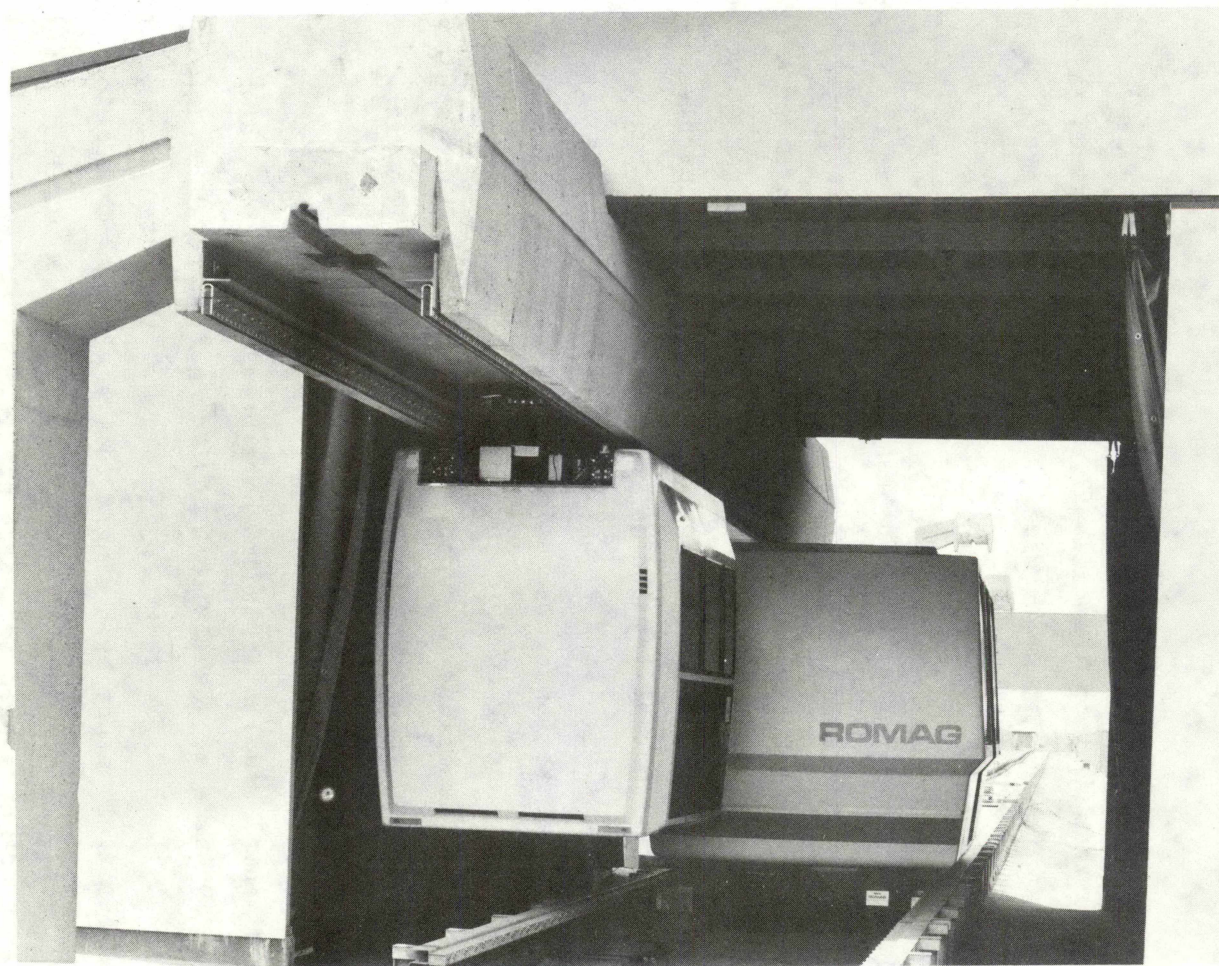


FIGURE 29  
ROMAG DEMONSTRATION VEHICLES (ROHR CORP.)

#### 4.0 REPULSION MAGLEV

Research in repulsion maglev has been the most extensive in Japan, where construction of a 500 km/hr test vehicle and 7 km of guideway are now underway.

The programs in Canada, West Germany, Japan and the US are discussed in this section. Additional work is being pursued in England at the University of Warwick.

#### 4.1 Canada

Experimental research in Canada has been conducted at the Canadian Institute of Guided Ground Transport at Queen's University. Efforts have been directed towards developing a vehicle operating over a flat topped elevated guideway. The flat topped guideway design was chosen to prevent ice and snow accumulation, which is a severe problem in Canada. For this concept levitation will be obtained by means of superconducting coils (placed along the side of the vehicle) traversing aluminum sheet tracks (under each side of the vehicle). A separate array of superconducting coils along the vehicle centerline is used for the combined functions of propulsion and guidance. Propulsion is by means of linear synchronous motor (LSM) winding in the track, while guidance is obtained by adding difference flux loops to the track.

Experimental studies in Canada have been carried out using a large (7.6 m) diameter wheel with a maximum peripheral speed of 100 km/hr. This wheel is shown in Figure 30. The large size of the wheel has permitted study of a single full scale superconducting coil with various track configurations. Both an LSM winding as well as a sheet track have been tested to date.



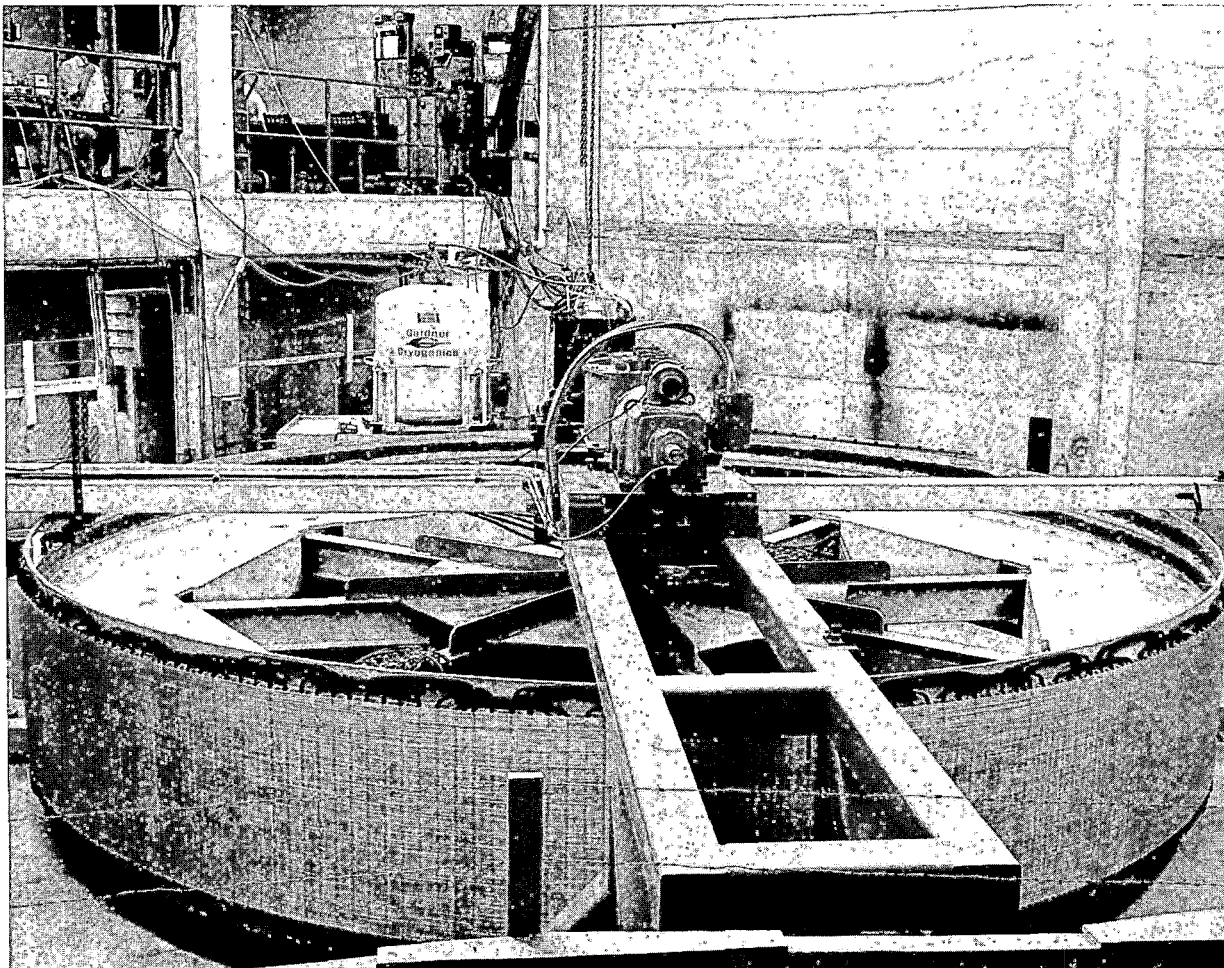


FIGURE 30  
ROTATING WHEEL FACILITY (QUEEN'S UNIVERSITY, CANADA)

#### 4.2 West Germany

An investigation of the repulsion maglev concept carried out by a collaboration of the companies AEG-TELEFUNKEN, BROWN-BOVERI and SIEMENS (AEG-BBC-SIEMENS) commenced in 1972. A circular test track of 280 m diameter was constructed in Erlangen, Germany (Figure 31). This track, sloped  $45^\circ$  inwards, permits maximum speeds up to 200 km/hr. The vehicle, 12 m long and weighing 12 tons, is shown in Figure 32. It was successfully levitated at a speed of 125 km/hr in March of 1976.

For suspension, there are two magnet carriers - one fore, one aft. Each carrier contains four superconducting magnets, two for lifting and two for guidance. The cryostats for the magnets utilize forced-flow cooling to account for problems arising from the steep banking of the track and centrifugal forces.

Propulsion has been by a double sided LIM with a vertical aluminum reaction rail, but plans now include replacing the LIM with a linear synchronous motor for propulsion.

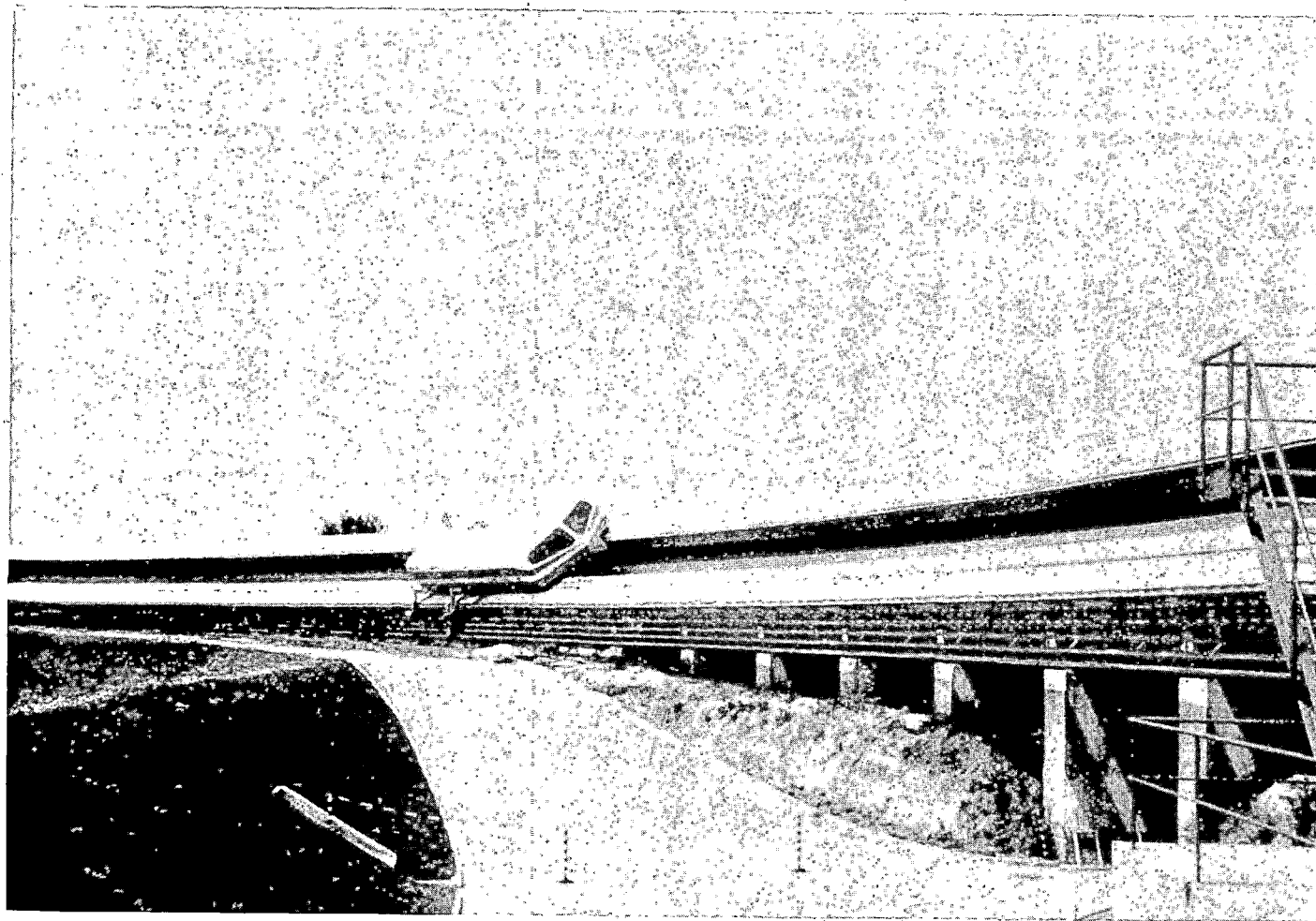
Recent work at Siemens has included rotating wheel studies of the control of the LSM. A large (5.8 m diameter) wheel constructed mostly of wood is being used.

#### 4.3 Japan

The Japanese effort to investigate a railway system to succeed the Shinkansen line started in 1962. Basic experiments were conducted concerning the LIM, air cushion suspension, and magnetic levitation by permanent magnets and normal electromagnets. This early effort indicated that linear motor propulsion coupled with magnetic levitation was a promising combination. In 1970 a small magnetically levitated linear motor driven vehicle was demonstrated at the World Expo '70.



FIGURE 31  
ERLANGEN TEST TRACK (AEG-BBC-SIEMENS)



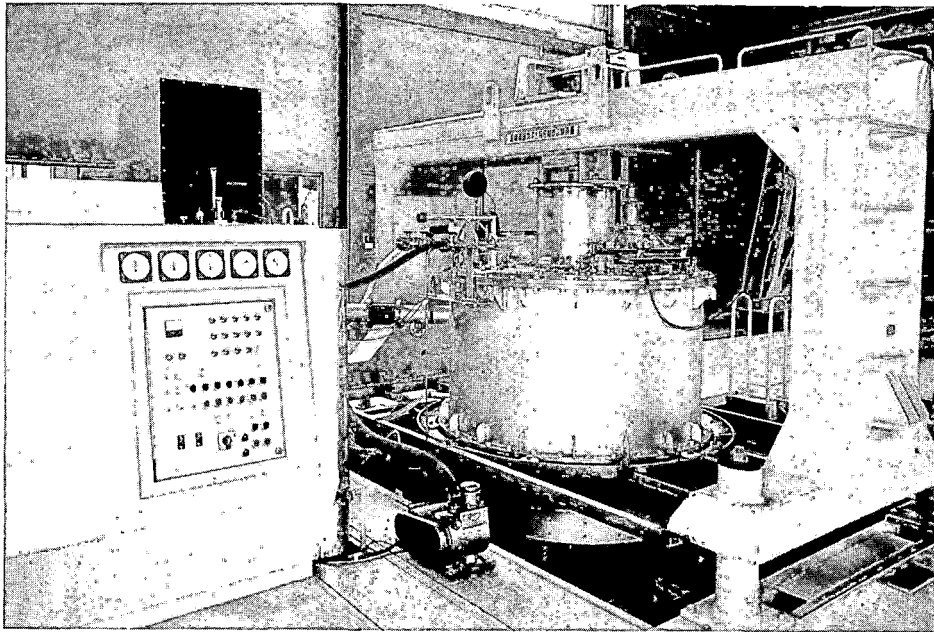
**FIGURE 32**  
**EET (ERLANGEN TEST CARRIER)**

In January 1970 a repulsion maglev vehicle concept using superconducting coils for lift and a linear motor for propulsion was given serious attention. Since the success of such a railway hinges upon the development of a vehicle-mounted superconducting magnet and its cryogenic cooling system, research was initiated.

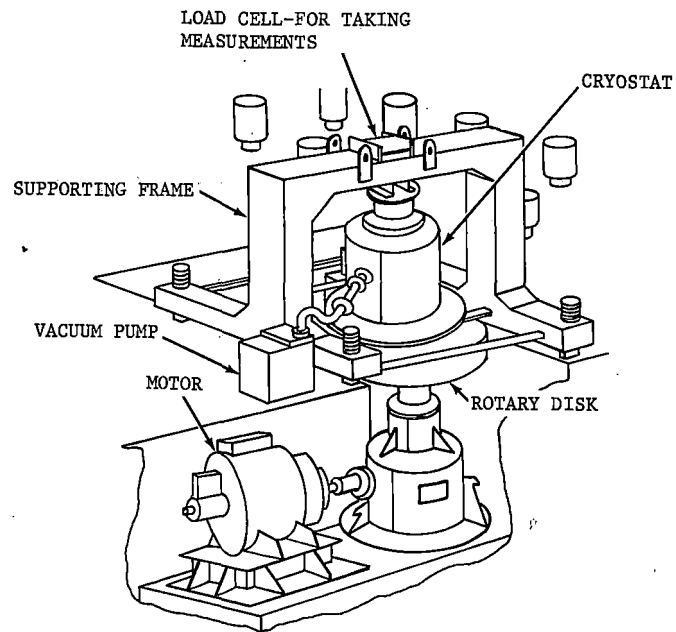
In 1970 a rotational test device, shown in Figure 33A, was built. The rotating disc, depicted in Figure 33B, was driven by an electric motor. The cylindrical cryostat contained two superconducting coils. The rotating disc simulated a moving guideway surface, the coils in the cryostat simulate the onboard vehicle coils. As a result of these experiments track coils, rather than a sheet track, were chosen as the preferred guideway conductor configuration. For the next stage of experiments a lighter weight superconducting magnet was developed and in 1971 successful levitation was demonstrated. Two full size cryostats and a trial lightweight helium compressor were also built in 1971. Further development of cryostats and refrigerators is still continuing at this time.

Two test vehicles were built and operated in 1972 to simulate and study the actual levitation and propulsion characteristics of a repulsion maglev system. The first vehicle, depicted in Figure 34, was propelled by a single phase LSM utilizing the fringe field of two superconducting magnets. The test track contained lift coils at the bottom and propulsion windings on the side walls. The actual vehicle and track are shown in Figures 35A and B. This vehicle was 4 m long and weighed 2 tons. The 200 m long test track permitted testing up to 50 km/hr.

A second vehicle, called the ML-100 (Magnetic Levitation JNR Centenary), was 7 m long and weighed 3.5 tons. This vehicle was propelled over a 480 m long track by a double sided linear induction

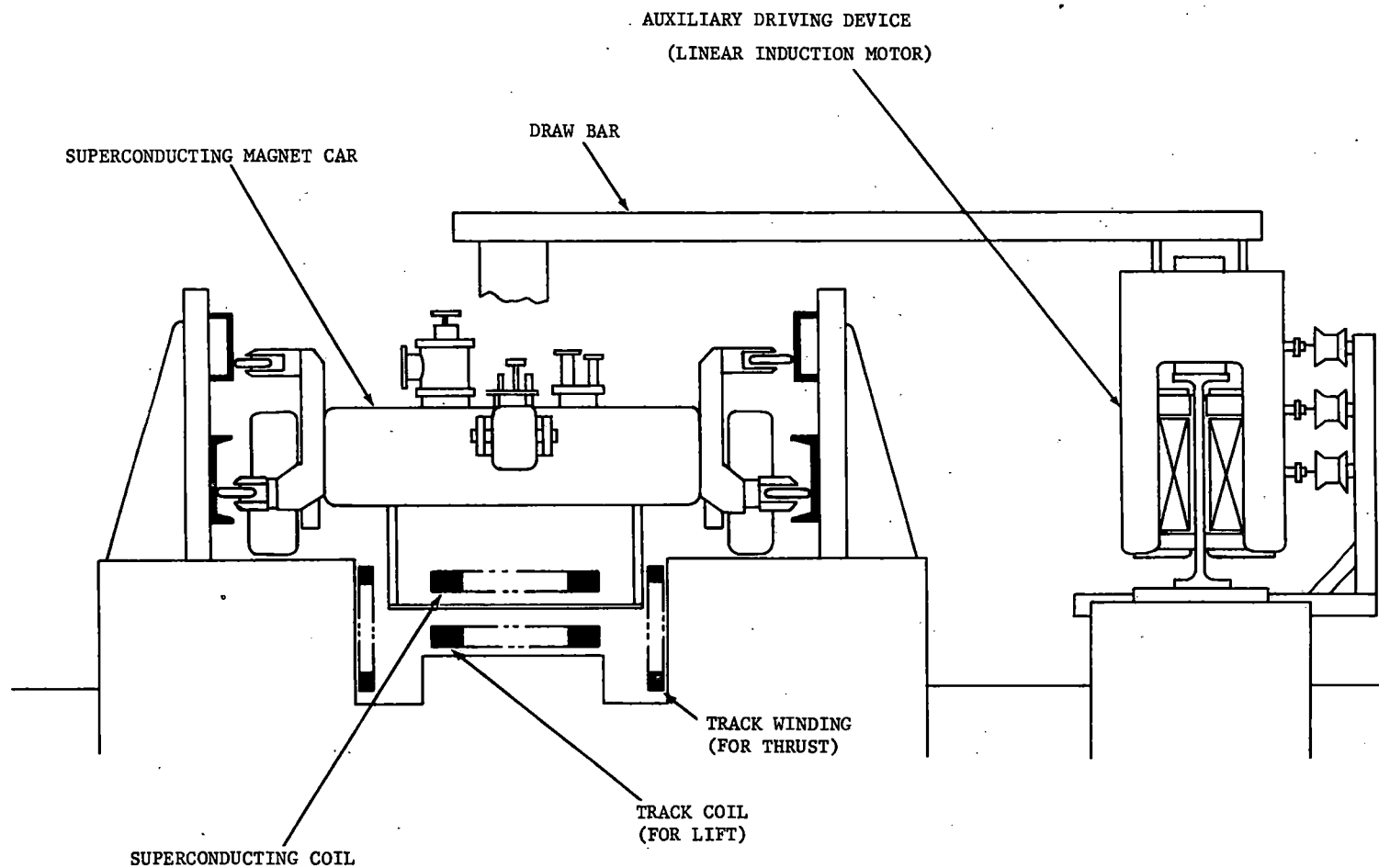


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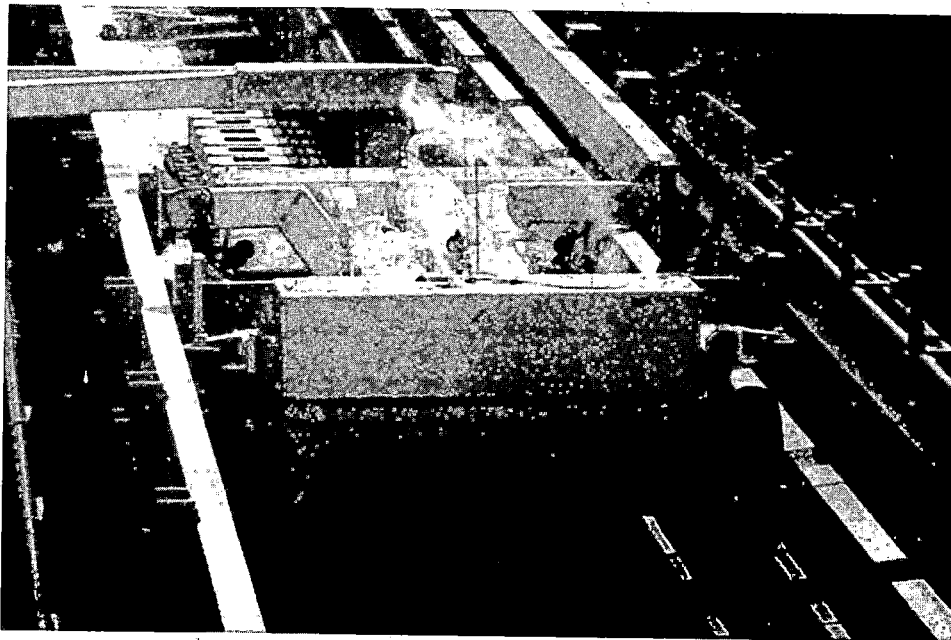


B

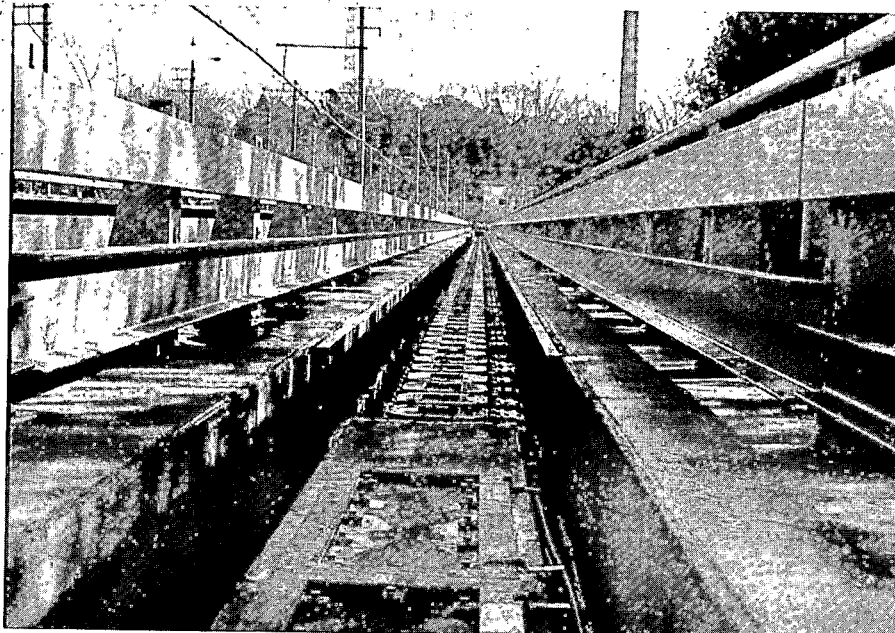
**FIGURE 33**  
**ROTATING WHEEL FACILITY (JNR)**



**FIGURE 34**  
**LSM TEST VEHICLE AND GUIDEWAY (JNR)**



A



B

**FIGURE 35**  
**LSM TEST VEHICLE AND GUIDEWAY (JNR)**



motor with the reaction plate on board. Figure 36 shows the actual vehicle. The track coil configuration is shown in the small model shown in Figure 37A. Figure 37B depicts a cross-sectional view of the vehicle. Note that the LIM reaction plate, attached to the vehicle, slides between two guide rails attached to the ground. Lateral guidance was by means of sliding shoes. This vehicle was tested at speeds up to 60 km/hr in September 1972.

In 1973 a rotating wheel facility (speeds to 150 km/hr) was constructed to test a combined propulsion/guidance system using an LSM with a null flux track winding. This configuration was chosen for further development as a result of these tests.

The ML-100 was then turned into a new experimental unit, called the ML-100A, shown in Figure 38. This vehicle is levitated by means of superconducting magnets traversing discrete track coils, as was the ML-100, but adds a combined propulsion/guidance system utilizing an LSM for thrust and a null flux track winding for guidance. Power for the LSM is from a cycloconverter. Figure 39 shows construction along the 151 m long track. The ML-100A has been tested at speeds to 60 km/hr.

Cryogenics is a critical issue for the feasibility of repulsion maglev concepts, and the Japanese have aggressively attacked this problem. Hardware studies have been directed toward the problems of minimizing cryostat weight and heat losses, while maintaining the ability to transmit the necessarily large suspension forces from the superconducting coil to the vehicle structure. Figures 40 through 43 show a few of the cryostats that have been developed in Japan. The W-1 wing type cryostat shown in Figure 40 was developed by Toshiba in 1972 for application to null flux lift or guidance applications. For these applications it is necessary to have the superconducting

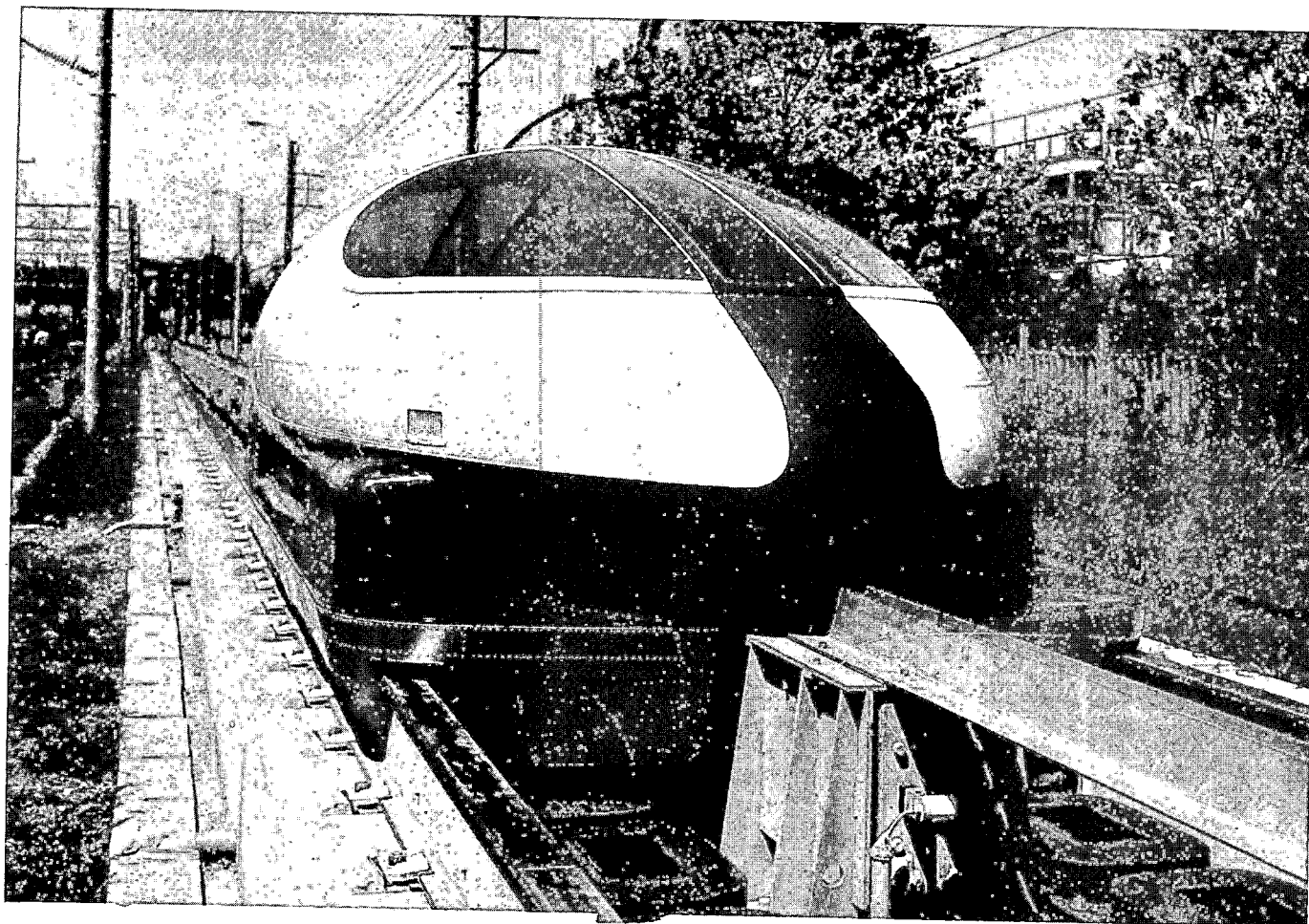
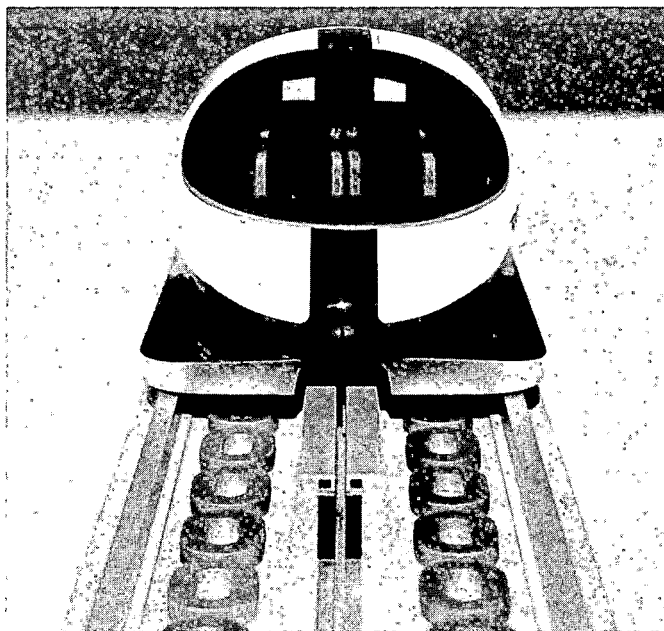
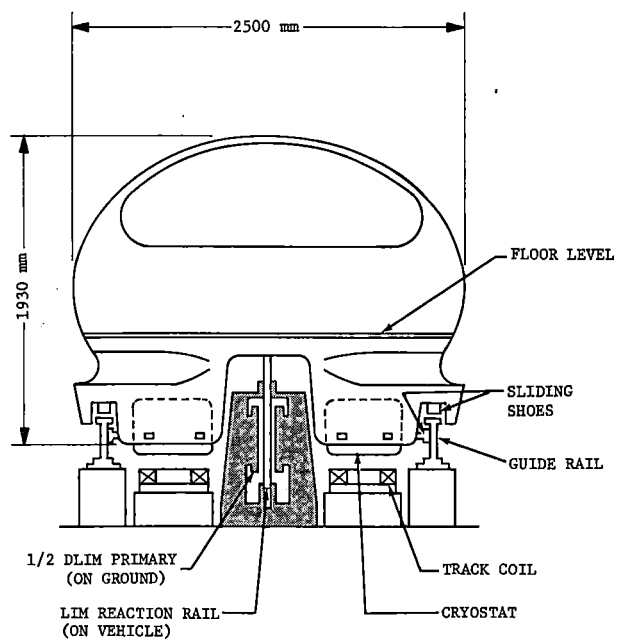


FIGURE 36  
ML-100 (JNR)

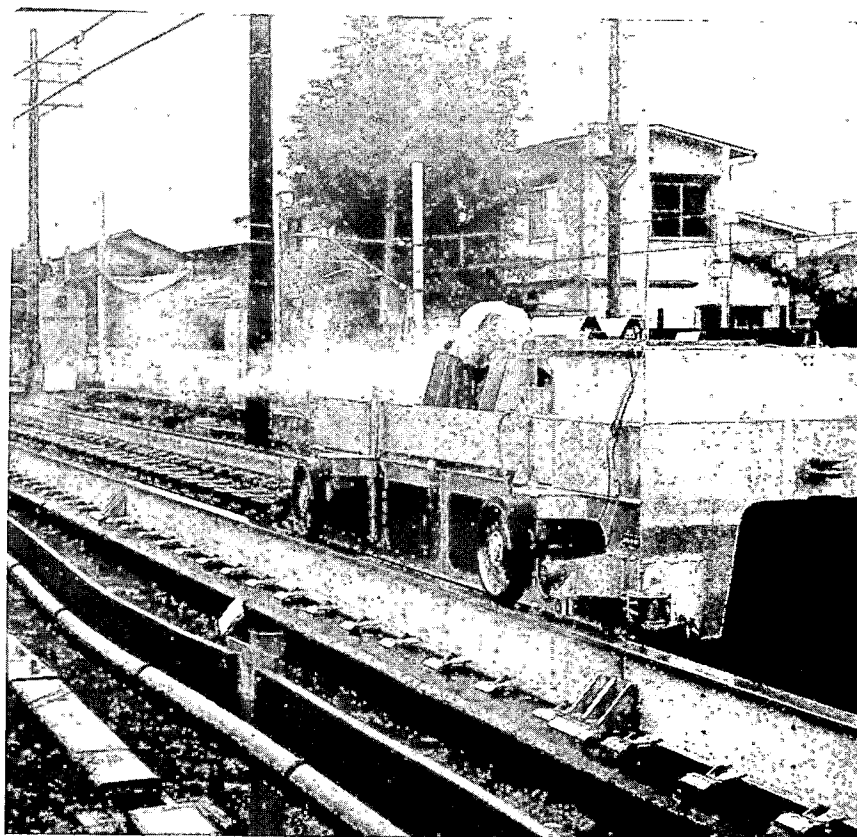


A



B

**FIGURE 37**  
**ML-100 (JNR)**



**FIGURE 38**  
**ML-100A (JNR)**



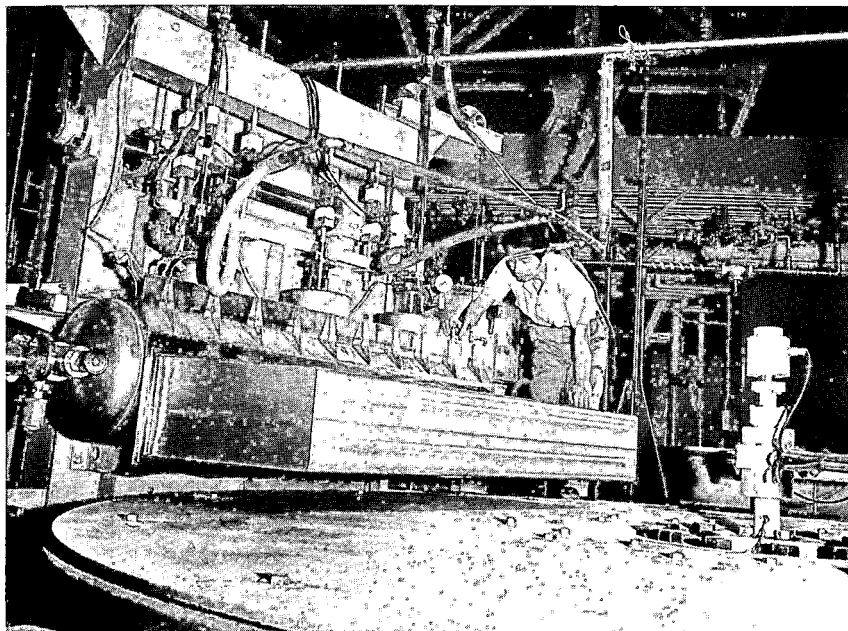


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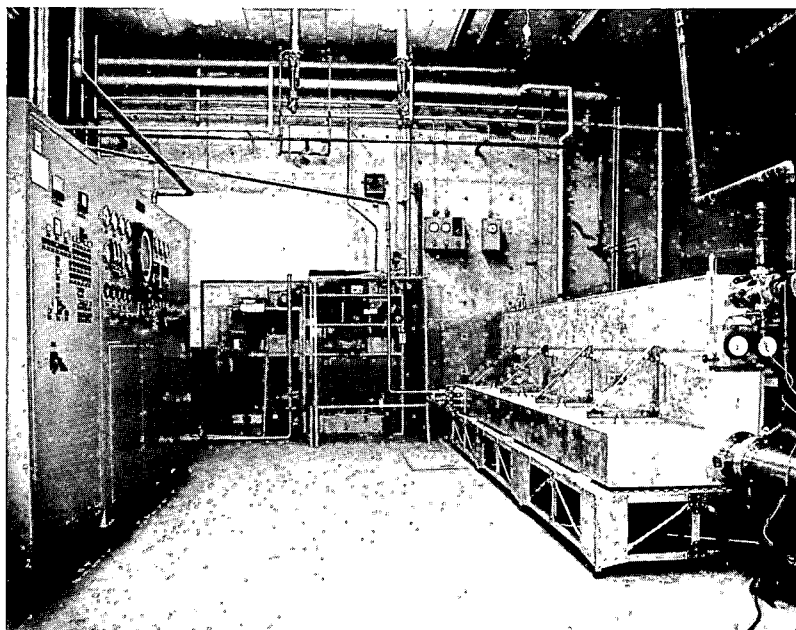


B

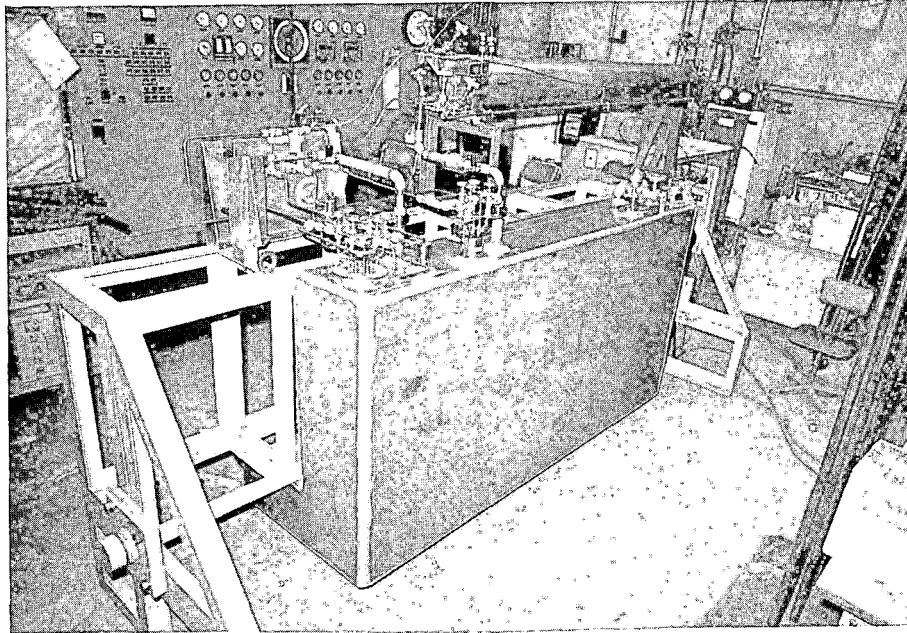
**FIGURE 39**  
**TEST TRACK FOR ML-100A**



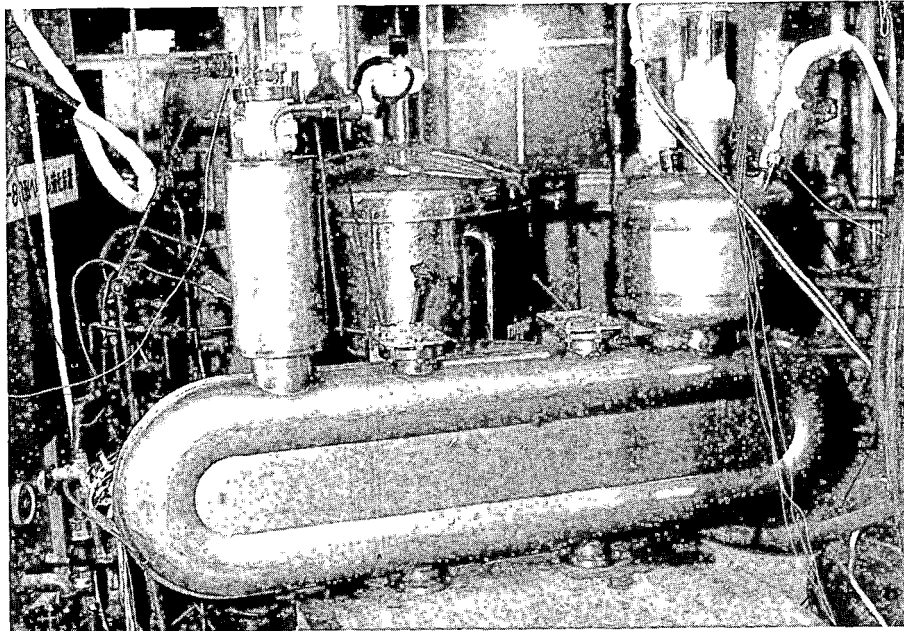
**FIGURE 40**  
**W-1 WING TYPE CRYOSTAT (TOSHIBA)**



**FIGURE 41**  
**L-1 L-TYPE CRYOSTAT (TOSHIBA)**



**FIGURE 42**  
**L-3 L-TYPE CRYOSTAT (TOSHIBA)**



**FIGURE 43**  
**PCM CRYOSTAT (MITSUBISHI)**



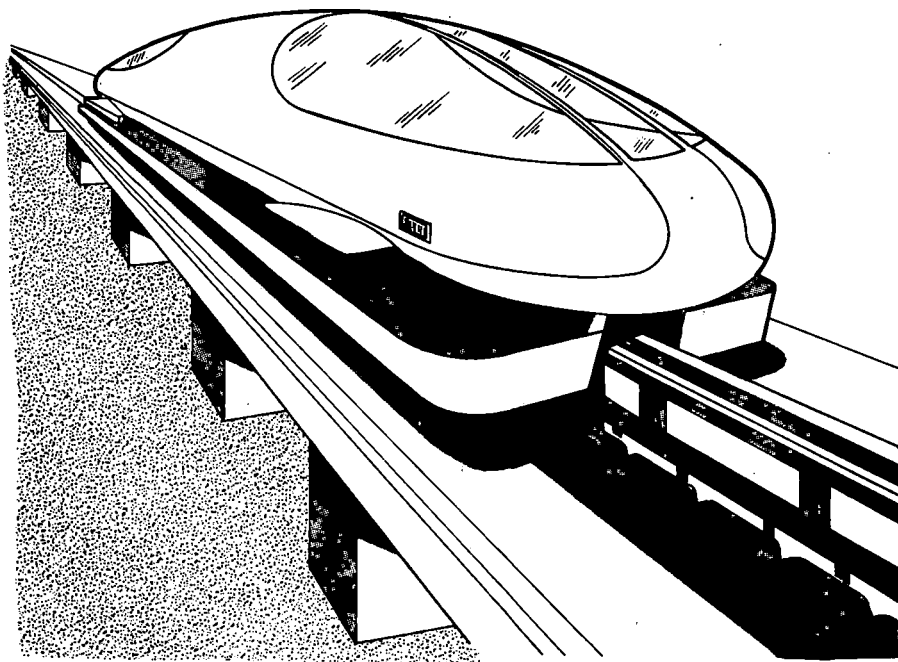
coil project into a thin wing so that the superconducting coil (inside) can be sandwiched between track coils on the outside. The rotating wheel used to test this coil is also shown in the figure.

Cryostats designated L-1 and L-3, shown in Figures 41 and 42, are designed to hold superconducting coils in both the horizontal and vertical planes. As can be seen from Figures 38 and 39, the horizontal coil is used for lift, the vertical coil for propulsion/guidance. Magnets of this general type were used on the ML-100A.

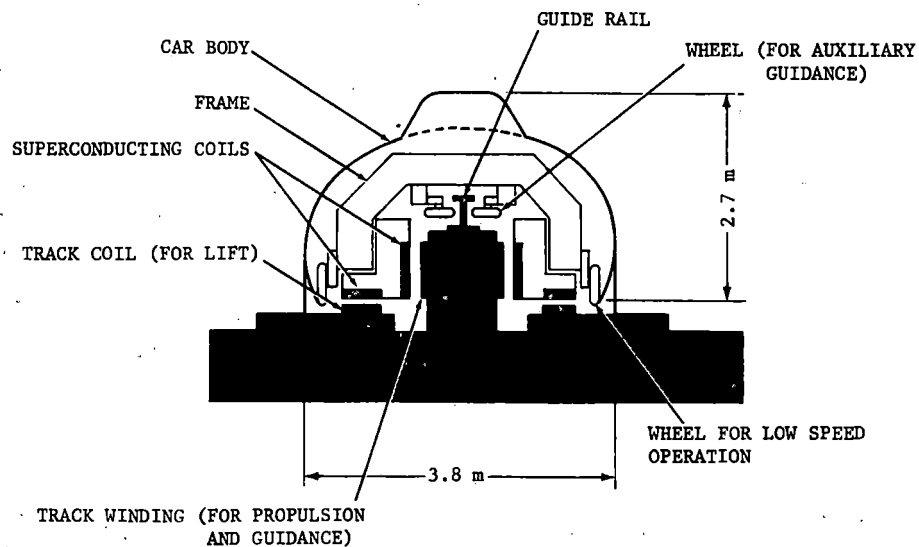
Figure 43 shows the cryostat designated PCM. This cryostat was designed to contain a single coil in the vertical plane for use in a propulsion/guidance configuration.

These research efforts have culminated in the design of a 7 km test facility that is now under construction in Miyazaki, Japan. Initial running tests began in July 1977 after the first 1.3 km of test track was completed. Due to the present length of the track, initial tests will be limited to 200 km/hr. The vehicle, intended to be a half-scale prototype, will eventually be tested at speeds of 500 km/hr when the track is completed. Designed after the ML-100A, the vehicle will be levitated over discrete track coils and will obtain both propulsion and guidance from an LSM with a null flux track winding connection.

Figure 44 depicts the planned vehicle configuration. The test track construction progress to date is shown in Figures 45A and 45B. The elevated guideway will be almost straight and level, 7 km long. Although an inverted-T structure is shown in Figure 45B, the mid portion of the inverted-T is demountable so that other structures can be tested. Both single and double piers are being tested, as can be seen in Figure 45A.



A

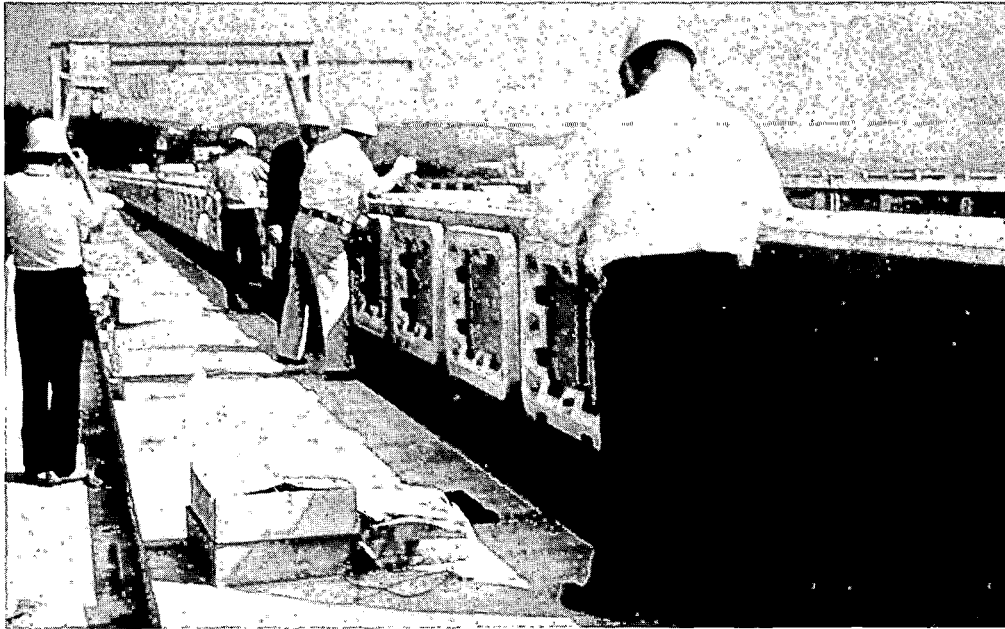


B

**FIGURE 44**  
**PLANNED CONFIGURATION FOR MIYAZAKI TEST TRACK**



A



B

**FIGURE 45**  
**CONSTRUCTION ON MIYAZAKI TEST TRACK**

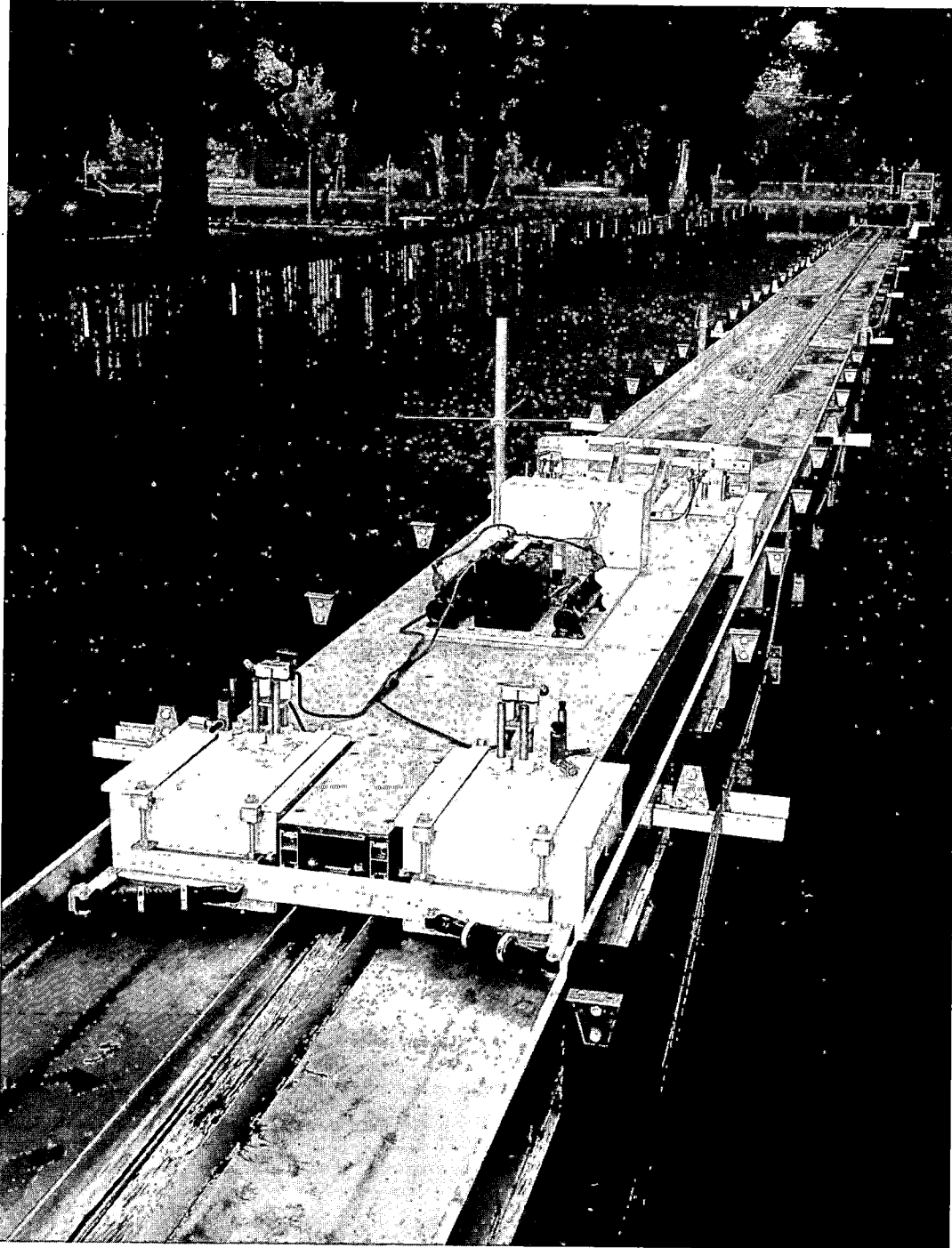
The tests at Miyazaki are critical to the maglev effort in Japan. If the results are promising, a 25 km test line will be constructed for full-scale operational tests.

#### 4.4 United States

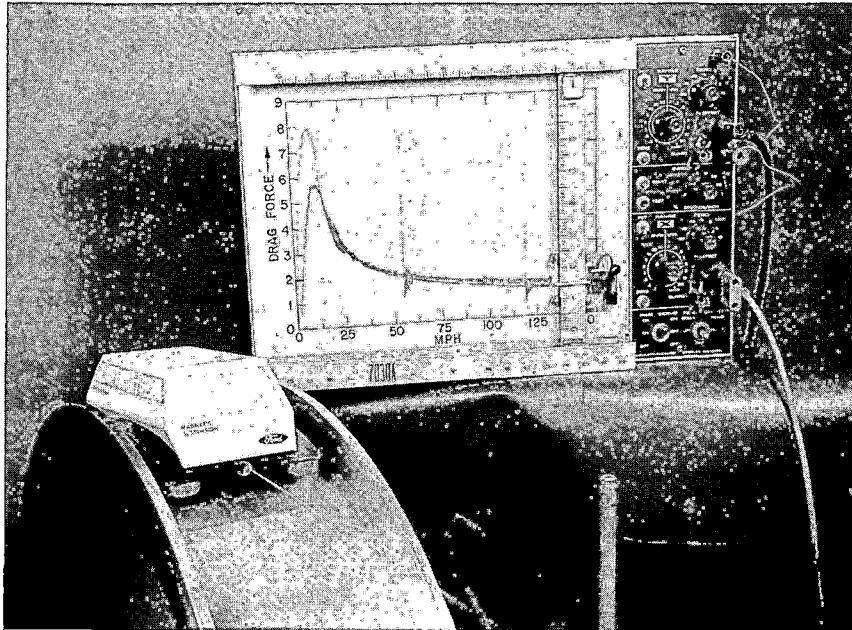
A small test sled that was levitated and guided by four superconducting magnets was constructed and tested at Stanford Research Institute from 1971-1973 under contract to DOT. This sled, shown in Figure 46, was moved by means of a cable from a glider towing winch. The SRI sled, 4.25 m long and weighing 296 kg, was tested to speeds of 42 km/hr on a 152 m long guideway.

Since 1970, members of the Scientific Research Staff of Ford Motor Company were also involved in the study of magnetic levitation for DOT. Calculations for the characteristics of coils moving over conducting plates were followed by a series of experiments using small rotating wheels of various diameters. The experimental setup for a 30.5 cm diameter wheel is shown in Figures 47 and 48. Figure 47 shows a small model vehicle utilizing permanent ceramic magnets levitated 6 mm over a rotating solid aluminum wheel. Figure 48 shows the experimental setup used to study a small cryostat containing a 5 cm by 10 cm superconducting coil. The cryostat is attached to force transducers for the measurements. Additional experiments were carried out with 61 cm and 1.5 m diameter wheels through April 1974. These studies were concerned with the performance characteristics of coils moving over conducting sheet and ladder tracks in channel guideway configurations.

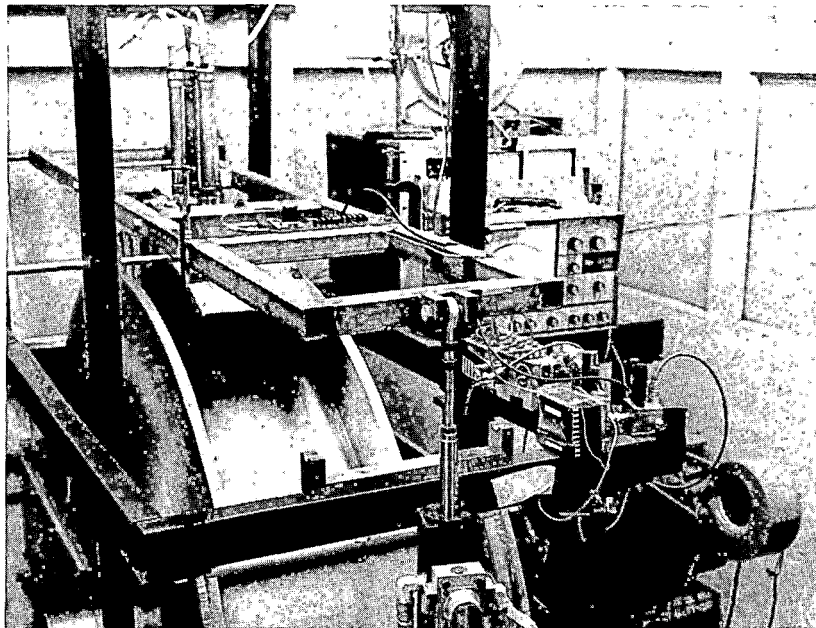
These small scale theoretical and experimental studies led to the start of a program to test a maglev sled accelerated by a rocket pusher. Although this rocket sled test program was terminated in January 1975 before the hardware was designed, a study of conceptual designs for revenue vehicles was completed. This study identified the



**FIGURE 46**  
**TEST SLED (SRI)**



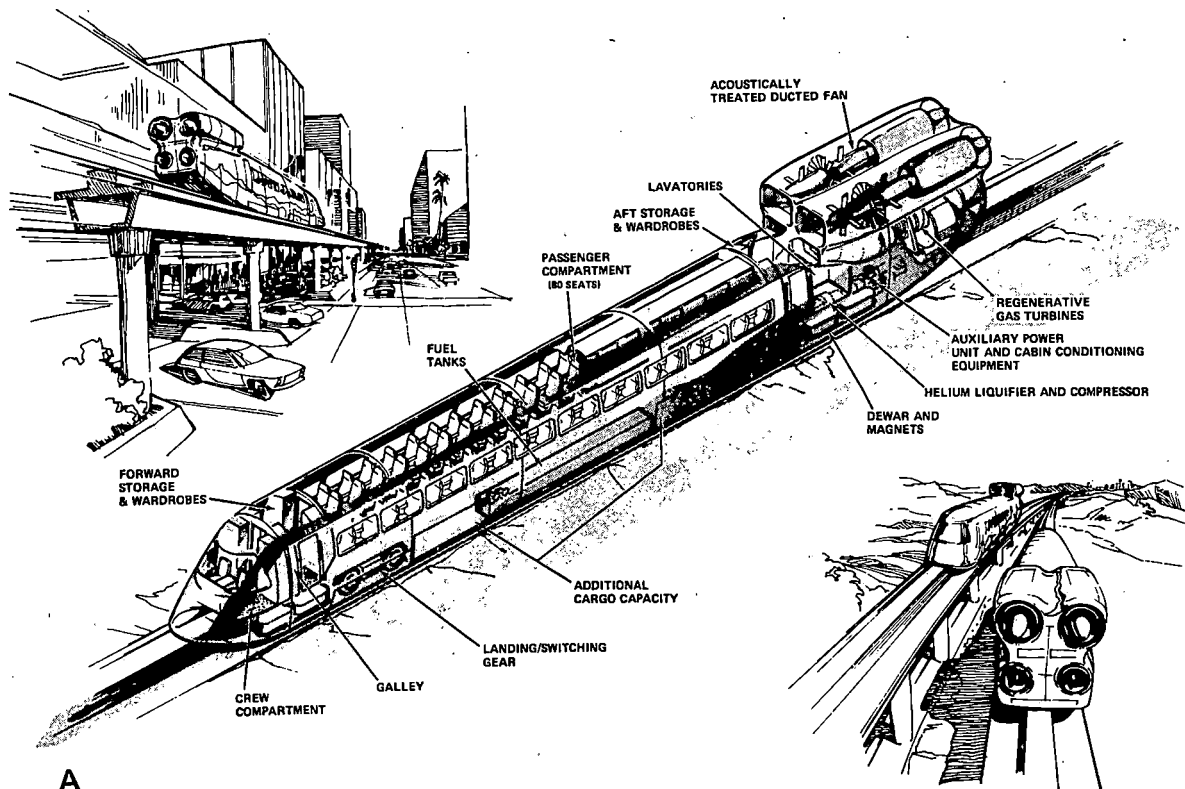
**FIGURE 47**  
**LEVITATION OF CERAMIC MAGNETS (FORD)**



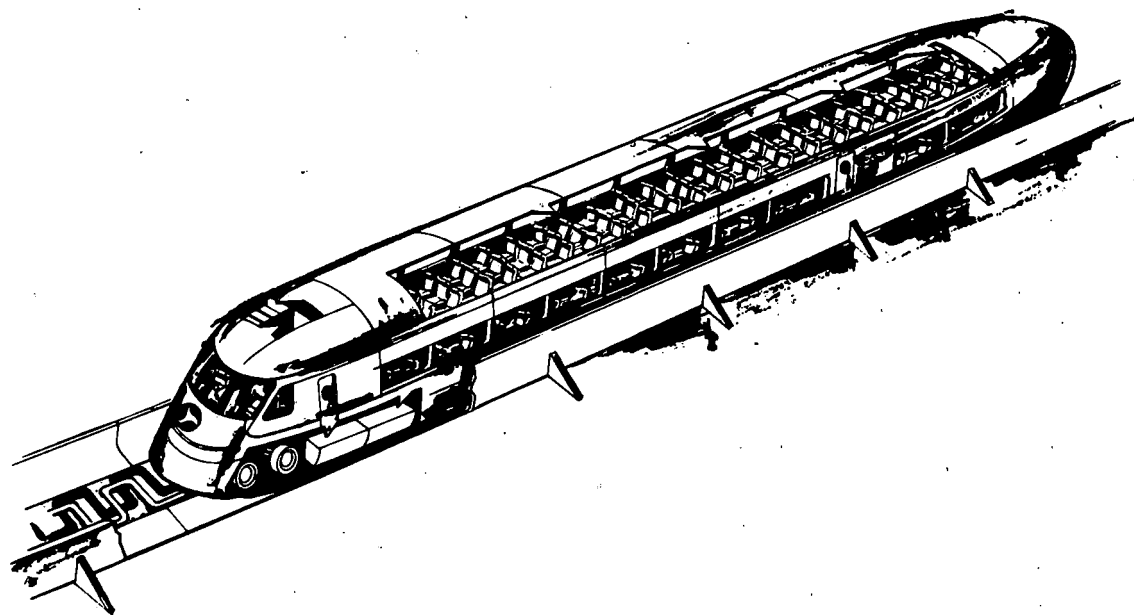
**FIGURE 48**  
**TESTS ON A SUPERCONDUCTING COIL (FORD)**

fluid propelled repulsion maglev concept shown in Figure 49A for near term implementation, and the LSM propelled scheme depicted in Figure 49B for longer term potential.

Efforts at the Massachusetts Institute of Technology (MIT), funded by the National Science Foundation, were directed towards investigating the magneplane concept. A small scale model, shown in Figure 50, was constructed and tested. In this concept, cylindrical vehicles travel in an aluminum trough, levitated and guided by superconducting magnets which extend under most of the lower vehicle surface. Propulsion is by means of an LSM track winding at the bottom of the guideway trough, levitation is by means of aluminum conductors on the sides of the guideway trough.



A



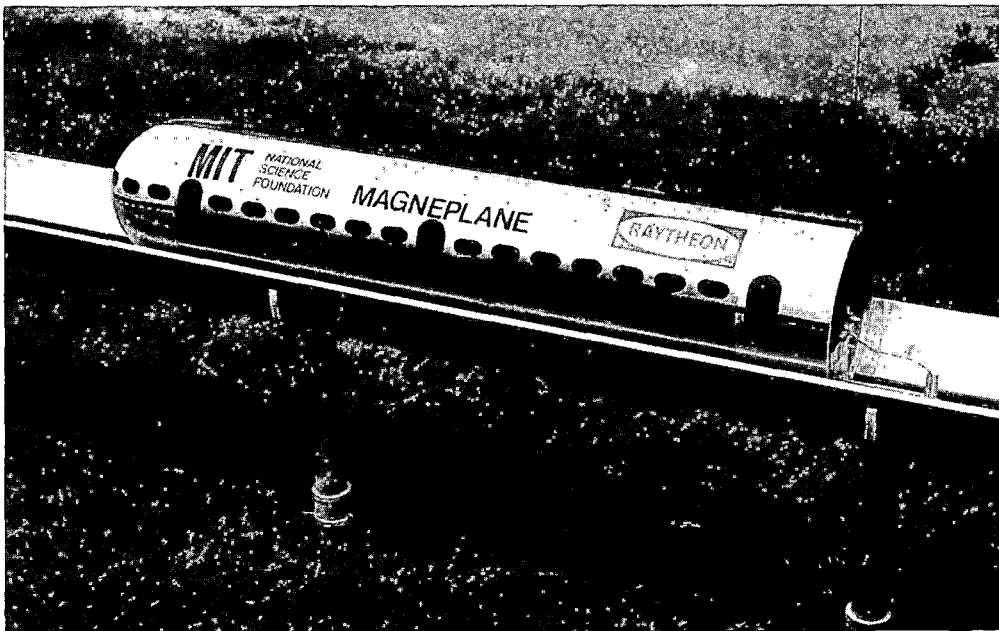
B

**FIGURE 49**  
**CONCEPTUAL VEHICLES (FORD)**





A



B

FIGURE 50  
MAGNEPLANE MODEL (MIT)

## **CHAPTER II**

### **TLV TECHNOLOGY STATUS REPORT**

## 1.0 INTRODUCTION

There are two purposes to this status report on the technology of noncontacting suspension schemes. The first is to briefly assess the status of the overall worldwide research efforts; the second is to identify the most critical areas of the respective technologies which require research. The object of this chapter is to tie the overall research into a framework which will serve to identify areas for further research. As such an assessment relies both on the information available in the published literature as well as that obtained during discussions with various members of the research teams involved, it solely reflects the opinion of MITRE/METREK.

This chapter is not intended to be a catalogue of the numerous research programs studied worldwide. On the contrary, various research programs have been discussed together whenever the basic physics and engineering required for their development were substantially the same. For example, rather than discuss the individual characteristics of the numerous coil/track geometries studied throughout the world for repulsion maglev, these concepts have been lumped together under the classification of normal, null, and difference flux methods. These three classifications were chosen since they each reflect system characteristics that are distinct from each other.

Comparisons between various components are usually easily accomplished, comparisons between systems seldom are. Since the application of ground transportation requires a complex integration of numerous components in an overall system, a comparison of components alone is academic. For example, the evaluation of the technology for an EDS system requires an evaluation of the overall cryogenic design.

However, an EDS vehicle with LSM propulsion requires a significantly more extensive cryogenic system than an EDS vehicle driven by a gas turbine/QFAN.

It is readily apparent that we wish to compare systems, not components. On the other hand, the technology tends to progress from components to systems, postponing an evaluation. For the case of EMS and air cushion suspension systems, the technology has been developed to the point where the systems are well understood. On the other hand, development of the component technology for the EDS system, delayed by virtue of the cryogenics required, is just now nearing the system level.

The intent of this assessment is not to make comparisons between systems or to choose one, but to provide the reader with a perspective of the overall development of the component technology, and the system implications of the component technology. This requires an evaluation of whether or not a conceptual design, made for a specific route, can be considered reasonably validated, or should be considered speculative. Future research can then be directed towards lessening the speculative nature in critical technical areas.

It is important to note that characterization in this report of a specific design as "speculative" or "optimistic" reflects only the status of today's technology, and is not intended as an adverse criticism of the concept. Such characterizations are only intended to identify features of existing conceptual designs which cannot be considered validated at this time.

## 2.0 AIR CUSHION

The air cushion suspension was the first noncontacting suspension to be developed to a practical level for a HSGT system, primarily as a result of the simplicity of its hardware. Several revenue vehicle prototypes have been demonstrated, the two most significant being the all electric DLIM propelled PTACV developed by the U.S. DOT, and the fluid propelled (gas turbine) High Speed Aerotrain developed by the Société-de l' Aérottrain in France. This technology is substantially validated for considerations of conceptual designs, hence will only be very briefly addressed here.

The most advanced suspension hardware developed to date, used on the PTACV and the High Speed Aerotrain, is the hinged lip plenum with an integrated flexible bag secondary. This suspension efficiently integrates a lightweight primary mass (for good tracking) and a secondary suspension (for good ride quality) in the hardware design. Demonstrations of the suspension to speeds of 430 km/hr have been carried out on the High Speed Aerotrain.

### 2.1 Static Air Cushion

The plenum chamber air cushion suspension has superseded the peripheral jet type, which had been the object of early work in Great Britain (RTV31) and in the U.S. (TLRV). It had originally been thought that the peripheral jet would lead to a lower power consumption design than the plenum chamber, but just the opposite proved to be the case. There is now wide agreement in the technical community on this point.

For a given air gap, the peripheral jet will require less power consumption than the plenum for lift and guidance (at standstill). However, for a given dynamic tracking performance the peripheral jet requires an air gap of 12-18 mm to protect the nozzle, whereas the

gap can be lowered to 3 mm for the plenum chamber by using the hinged lip plenum. By reducing the air gap the air flow decreases substantially, which leads to a considerable reduction of both the compressor power and the captation drag. Small scale testing of both concepts carried out at KM verified these conclusions [1].

In terms of the analysis, good agreement between theory and experiment has been found. Analytical work at MIT is typical of the state-of-the-art in this area.

## 2.2 Dynamic Air Cushion

Small scale research on the tracked ram air cushion concept is being carried out by TSC in the U.S. A conceptual design study has also been carried out [2]. A significant development effort, however, would be required to prove the performance of this scheme in a HSGT system.

### 3.0 ATTRACTION MAGLEV

Attraction maglev research to date can be placed into two major categories, these are:

- a. separate suspension/propulsion (EMS + LEM)
- b. integrated suspension/propulsion (uses only a LEM)

Separate suspension/propulsion refers to systems using conventional DC electromagnets for lift and guidance and a linear electric motor for propulsion. This is referred to as EMS suspension and LEM propulsion.

Integrated suspension/propulsion systems (ISPS) are a "second generation" development of the propulsion motor. They require the control of inherent motor forces for simultaneous suspension and propulsion in the same machine. They do not use separate DC electromagnets.

The following sections will briefly discuss the status of these systems to date.

#### 3.1 Separate Suspension Systems (EMS)

There are two major types of EMS suspension systems. These utilize:

- separate lift/guidance magnets, or
- combined lift/guidance magnets.

Separate L/G magnet systems have been demonstrated by MBB in the FRG (Magnetmobil, KOMET, KOMET M) and by the MOT in Japan (EML-50). These systems utilize an L-shaped iron track on each side of the vehicle. Lift and guidance are obtained from separate U-shaped magnets whose poles face the horizontal and vertical sections of the L, respectively. The magnets used are of the transverse flux type. The two primary characteristics of this system are:

- a. it allows high guidance forces to be developed (to 1 g for unsprung magnets), and
- b. it allows independent control of lift and guidance.

An alternative scheme, using combined lift/guidance magnets, has been demonstrated by KM in the FRG (TU-02, TR-02, TR-04) and by JAL in Japan (HSST-01). In this configuration a pair of transverse flux U-shaped magnets are staggered laterally with respect to the longitudinal centerline of a U-shaped iron track, each magnet providing both lift and guidance forces. For small nominal guidance forces, this system has an advantage in weight compared to the separate L/G system. The crossover point, above which the combined system has a weight penalty, depends on the overall magnet design, i.e., the gap chosen and vehicle loading, and cannot be absolutely determined. However, a general estimate can be obtained by noting that for unsprung magnets, a Ford study [3] shows the crossover to be about .3 g, while a Transrapid-EMS study [4] reportedly places it between .3 to .5 g's. In either case, it is generally acknowledged that the lateral tracking ability of the combined system is somewhat limited compared to the separate L/G system.

An additional characteristic of the combined system is that the lift and guidance are inherently coupled, providing a limited region of control. The lift limits the guidance. For example, if such a suspension were to traverse a steep downward incline, the control system would cause all the magnet currents to decrease, thus reducing the lift. This allows the vehicle to fall, hence it can follow the guideway. This in turn limits the lateral force, hence a tight turn could not be negotiated simultaneously with a downward grade. It should be noted that this limit merely illustrates a lower tracking ability in general, it does not imply that this system is not the better choice for a given application.



The design, performance and tradeoffs of independent suspension for attraction maglev systems have been advanced to a high degree. Conceptual designs using the results of this research can be considered validated in the following critical areas:

- lift to weight ratio of magnets (air-cooled)
- current/force characteristics (both DC and AC)

These relate to defining the limits on lift/weight placed by magnet saturation effects and limits on controllability placed by the nonlinear magnet force law and magnet eddy currents. These critical areas proved to require extensive experimental verification of the analysis.

In summary, both the separate and combined L/G systems have been extensively investigated analytically and experimentally, and reliable conceptual designs have been developed.

#### 3.1.1 Control Systems

The area of magnet/vehicle control is also well understood, but it tends to be vehicle/guideway specific and must be evaluated for each case in practice. The area of controls, however, is highly advanced and although development can be arduous, good results can be anticipated.

It is important to note that there are well defined physical limits to the tracking ability of an EMS maglev system, and although these limits can be steadily approached by advanced control system techniques, they cannot be exceeded. These limits on the tracking ability are imposed by the:

- magnet force laws, and the
- sprung to unsprung mass ratio of the suspension.

The magnet force law limits the tracking ability because magnet flux leakage and saturation effects limit the force which can be developed. The maximum force obtainable (for a given magnet at a given gap) is limited by magnet saturation, and this force decreases as the gap increases (due to flux leakage). Magnets are usually roughly designed to provide a maximum of twice the nominal lift at nominal gap, and only the nominal lift at twice the nominal gap.

The sprung to unsprung mass ratio limits the tracking ability because it limits the magnet accelerations obtainable. If the magnets are not sprung they cannot track at more than 1 g ( $9.8 \text{ m/sec}^2$ ). If the magnets are independently sprung they can track with higher accelerations, allowing rougher guideways.

Once the magnet force laws are known, as they now are, upper limits to the tracking ability can be reliably imposed. Control system design, though necessary for implementation, is therefore only important in the vein of realization and optimization. The critical area for valid predictions of a conceptual design is that of magnetics, not control.

The design of the control system is crucial, of course, to the design of the vehicle, but its success can be anticipated. For this reason, the details of control system progress are of a practical but not critical nature. Suffice it to say that numerous control system schemes are being studied and developed in order to verify and optimize the tracking ability of the vehicle. The areas studied include control problems arising from

- flexible vehicles
- flexible guideways
- trained vehicles
- separate and combined L/G magnet configurations

- control in turns, grades
- number and type of motion/gap sensors
- independent magnet (decentralized) vs. multiple magnet (centralized) control
- hierarchy of control logic (for safety and system checkout)

This work has been done primarily in the FRG although substantial work has also been done in other countries.

Single magnet control is being pursued by Transrapid-EMS in the FRG and by MOT in Japan, where each magnet is controlled primarily by its own sensors. Multiple magnet control has also been studied in the FRG, where the observations of several vehicle sensors are resolved by the control logic into individual degrees of freedom. In multiple magnet control, the control system employs banks of magnets (at appropriate vehicle locations) to control the modes. Either of these techniques will work.

An extensive breadth of knowledge is building in the area of controls, yet further studies are still necessary before an optimum system is realized.

An additional type of the EMS suspension that has received recent attention is that of independently sprung magnets. The advantage of this scheme is to improve the sprung to unsprung mass ratio, allowing increased tracking ability. This scheme is a planned modification of the lift magnets on MBBs' KOMET in the FRG. The modified vehicle, designated the KOMET M, will be tested in late 1977. If the design of this configuration proves to be workable, reliable and compatible with the propulsion LEM, it will undoubtedly outperform the earlier approaches. A brief description of this system follows:

### 3.1.2 KOMET M

The KOMET M is based on a modular magnet structure with decentralized control system logic [5]. The levitation and guidance magnets are modularly arranged in bogies. The magnets are suspended from the bogies by both plate-springs and pneumatic springs. The bogies are coupled by hinges and attached to the cabin by a secondary suspension. For this type of suspension the number of magnets per bogie and number of bogies per cabin can be determined to optimally track the guideway anticipated.

The decentralized control system logic is based on two levels:

- Level 1 consists of the single magnets, each utilizing information from its own gap sensor, accelerometer and current measurement.
- Level 2 consists of autonomous functions as:
  - banking of the cabin in curves
  - accommodation to static load changes
  - control of "take off" and "landing" of the vehicle
  - monitoring
  - failure identification
  - check out

Level 2 logic relies on centralized processing of information from several sensors. All control and monitoring will be realized by microprocessors. The advantages of the KOMET M configuration, as regards magnet control, can be stated briefly as follows:

- The low secondary suspension frequency provides sufficient decoupling between the magnets and the body to mitigate problems associated with structural elasticity.
- Improved ride quality.
- Independently sprung magnets can track in a more nearly optimum manner, as they allow more flexibility in the design.

### 3.1.3 Rail Eddy Currents

The issue of the amount of magnetic drag and loss of lift for transverse flux magnets due to rail eddy currents has received a considerable degree of analytical and experimental attention, as a result of the analytical difficulties involved. The problem has apparently led to a complete, nonlinear solution of Maxwell's equations by numerical methods at Transrapid-EMS in the FRG.

It is important to realize that these eddy currents can be prevented by using a laminated rail. (Whereas the EDS suspension requires track eddy currents for lift, the EMS system does not, hence the associated problem can be eliminated for the EMS system.) The issue of cost of lamination has not yet been resolved, but there is no strong evidence to indicate that a laminated rail is significantly, if at all, more costly. In any case, if eddy currents are significant for a given application, they can always be eliminated by using a laminated rail. Although verification of the extent of the problem is essential before a system is installed, it is not a critical issue at this time. This matter can wait to be resolved until overall optimization is necessary.

The EMS schemes discussed previously (MBB, KM, MOT, JAL, etc.) were of the transverse flux type. Transverse flux magnets (with equal excitations) can be made to have a long "effective" length, hence less drag, merely by placing them end to end (separations of up to a few centimeters are allowed). The long effective length will likely reduce the drag to the extent that track lamination will not be required, but this will have to be further verified in the field as there the current in adjacent magnets can vary substantially.

It is interesting to note that use of a laminated track is being proposed at Derby [6] in England for an EMS attraction maglev scheme

being studied there. This scheme uses longitudinal flux magnets which inherently require a laminated track to reduce drag. (Longitudinal flux magnets, as those proposed at Derby, cannot have an effective length greater than a single magnet length. Furthermore, since their length is proportional to rail thickness, they must be kept short, hence a laminated track is required.)

#### 3.1.4 Miscellaneous Magnet Configurations

The most well known magnet configuration is the transverse flux U-shaped magnet, working against a flat or a U-shaped rail. Other geometries briefly considered by some workers are the longitudinal and transverse E-shaped DC suspension magnets.

The longitudinal flux E-shaped DC suspension magnet was studied both in Britain (British Rails Research Department at Derby) [6] and in Canada (at the University of Toronto) [7]. The transverse flux magnet was studied in the FRG [8].

#### 3.2 LEM Propulsion for EMS Systems

Although this report is primarily concerned with suspension systems, a conceptual design must provide for the design of a compatible propulsion system. In addition, the second generation development of LEMs has led to the integration of propulsion and suspension into one machine. For these reasons it is important to consider the existing propulsion system research as integrated with the suspension research. The purpose of this section is to describe the status of the propulsion system development for those LEMs which also have potential for application in an integrated suspension/propulsion system (ISPS) mode.

LEMs are categorized here first as to their means of power collection (power collector or active track), as this has the largest overall system implication. The major categories are therefore:

- passive track (primary winding is on the vehicle, hence it uses a separate power collector), and
- active track (primary winding is in the track, hence it has noncontacting power collection).

Within these categories both linear induction and linear synchronous motors are possible. The passive track motors considered to date are the:

- LIM (SLIM and DLIM), and
- LSM (claw pole and homopolar inductor).

The only active track motor considered is the

- Iron Core LSM.

Before turning to the LIM and LSM, the system implications involved in the choice of an active track vs. a passive track motor will be discussed.

### 3.2.1 Power Distribution/Collection: Active Track vs. Passive Track

There are three major implications for the overall system that reflect the choice of passive vs. active track. They are:

- construction/maintenance costs
- type of power distribution (AC or DC)
- type of power conditioning (inverter, etc.)

A discussion of these follows.

#### 3.2.1.1 Construction/Maintenance

The issue of relative cost of an active track compared to a passive track power collector is far from resolved.

Although not yet fully developed, it is reasonable to assume that a brush/rail type of power collector can successfully be used at speeds

to 500 km/hr, but its cost will undoubtedly be substantial. This cost reflects the power rails which must be installed in a manner compatible with supporting a high speed brush tracking assembly.

A case for the active track is made by virtue of the fact that the track windings may not utilize any more conductor than the power rails for a passive track, and their installation may not prove to be significantly more complex. This has not yet been shown, since a workable active track system with an excitation voltage low enough for conventional cables must be better defined. In addition, the construction/installation costs of such a system are not well known. Furthermore, these costs are not directly comparable to the costs of a passive track since the issue of AC vs. DC power distribution also enters the picture. Active track systems require low frequency AC distribution, passive track systems appear best with DC distribution.

#### 3.2.1.2 Type of Power Distribution

Either passive track or active track LEM's can utilize AC distribution. Active track schemes require AC distribution to eliminate an onboard power converter. Passive track systems, however, pay a substantial onboard weight penalty if AC distribution is required. The nature of this penalty is a requirement for an onboard rectifier to convert the AC from the mains to DC for the inverter/LEM.

At the present time only AC distribution is feasible at the voltage levels optimum for an HSGT system. DC systems, however, are expected to be developed within the next decade. For purposes of planning, therefore, the evolution of high power DC distribution must be strongly considered. In fact, conceptual design component weights for passive track inverter/LEM systems cannot be fairly evaluated without checking whether AC or DC distribution was assumed.



In anticipation of the development of high power DC distribution by industry, passive track LEM systems can be considered with the assumption of DC distribution, active track LEM's with AC distribution. Since the techniques and costs of AC and DC distribution can be different, this complicates an absolute comparison between active and passive track installation costs.

Detailed designs for active tracks are not yet well established; the costs, therefore, are not well known. There is still some uncertainty as to the voltage levels and frequencies that must be accommodated by the distribution system. Further systems studies will be required before block lengths, voltage levels and frequencies can be optimized in terms of overall system costs for an active track system.

The costs for DC distribution for passive track systems are not well known either. The technological components for a DC distribution system at the voltage levels optimum for an HSGT system are not yet developed.

Another important aspect is the method of power conversion used for conceptual designs. To insure high system efficiency both passive and active track systems require variable voltage, variable frequency (VVVF) excitation. This requires some sort of power conversion, or power conditioning unit (PCU). This also has important system consequences, as discussed next.

#### 3.2.1.3 Power Conditioning

The power conditioning for passive track LEMs is done onboard with an inverter as frequencies required by a VVVF excited LEM (100-400 Hz) are too high for AC distribution techniques.

Previously constructed LEMs utilizing 50-60 Hz AC distribution required heavy, onboard rectifiers, as discussed in the previous section. Even assuming that DC distribution becomes available, eliminating the rectifier, the inverter will still be a major source of onboard weight. Present trends in inverter design may, however, be expected to lead to further inverter weight reduction. As an example, one can consider the means of commutation used to switch off the thyristors in a thyristor inverter. Either

- forced commutated or
- load commutated

designs are possible. The TLRV for example, used a heavy, load commutated inverter because suitable power capacitors at the required power level were not available at the time. Such capacitors are now being made available by industry, hence future lower weight designs of the forced commutated type are now feasible.

Another possibility for inverter weight reduction may develop in the next decade. This is the development of transistor inverters at the power levels required for an HSGT vehicle. Such a development may occur, and would significantly reduce the PCU weight (by eliminating the need for the commutation capacitors required by thyristor inverters).

It should be noted that a light weight transistor inverter is used on the ROMAG low speed combined suspension/propulsion SLIM at Rohr Corporation. However, even though this transistor inverter is within the state-of-the-art at the power levels necessary for low speed, extrapolation of this inverter to a high speed conceptual design is optimistic at this time.

In contrast to the onboard PCU required by a passive track LEM, an active track LEM requires wayside power conditioning. A variable voltage, variable frequency power conditioner must excite the track

windings in such a manner as to provide closed loop control of the vehicle motion. This requires a control communication link between the vehicle and the power conditioning substation. Studies concerning the control and power conditioning are underway, yet are far from complete.

In summary, present day state-of-the-art hardware leads to pessimistically heavy onboard PCUs for passive track LEM conceptual designs. Techniques such as water cooling, use of forced commutated thyristor or development of high power transistor inverters, and development of high power DC distribution hardware may well be expected to alleviate this problem. Much remains to be studied, however, before reliable estimates of cost/performance tradeoffs can be made for either passive track or active track LEM's.

A discussion of propulsion LEMs of interest follows. Passive track LEMs are discussed in Section 3.2.2, and active track LEMs will be considered in Section 3.2.3. LEMs used for combined propulsion and suspension are discussed in Section 3.3.

### 3.2.2 Passive Track Propulsion Machines

Both LIM and LSM designs are being studied for passive track applications. Section 3.2.2.1 discusses the LIM, Section 3.2.2.2 discusses the LSM.

#### 3.2.2.1 Linear Induction Motors

Two configurations for the longitudinal flux LIM have been studied, the double sided, or DLIM, and single sided, or SLIM. The design of the air cooled LIM is now well understood, and can be considered thoroughly validated. Predictions of performance can be made with good confidence. Some degree of uncertainty, however, apparently still exists in the technical community concerning the choice between a SLIM and a DLIM. At this time, the SLIM appears to be the better choice, the basic

argument being that the DLIM reaction rail presents mechanical problems as it requires a relatively thin aluminum rail to be edge mounted on only one side. It is also subject to thermal expansion/contraction problems. The SLIM reaction rail overcomes these problems. The disadvantages of the SLIM, however, are as follows:

- higher cost for reaction rail materials
- slight performance degradation

In either case, reliable conceptual designs for the performance of a LIM can be constructed. The outstanding uncertainty for the system lies in the associated inverter weight, as discussed in Section 3.2.1.3.

Although not of a critical nature, an important aspect of LIM optimization lies in the area of liquid cooling. Since the electrical, magnetic and thermal loading are all related, liquid cooling opens up another area of LIM design flexibility. Such studies in this area are appropriate for all LEM's.

#### 3.2.2.2 Linear Synchronous Motors

The primary advantage of synchronous motors compared to induction motors is their inherently good power factor. For the HSGT application, where vehicle power levels can be as high as 10 megawatts, this is a significant advantage and has led to considerable development of the LSM in recent years.

The claw pole and homopolar inductor (iron core linear synchronous motors) are the subject of an experimental research program now being conducted at GE, sponsored by the FRA. After preliminary comparative studies, the GE work was focused on the homopolar inductor. The

results of this study should be available in late 1978 at which time further evaluation can be conducted. Siemens recently studied the homopolar inductor for application in the ISPS mode, but it was dropped in favor of an active guideway LEM.

### 3.2.3 Active Track Propulsion Machines

The uncertainty as to the practicality of high speed ( $> 300$  km/hr) power collection has contributed to the interest in active track machines. The most extensive development of an active track machine for attraction maglev has been conducted at Transrapid-EMS where the iron core LSM is being studied. The result of this research is just becoming available at the time of this writing.

### 3.3 Integrated Suspension/Propulsion Systems

The use of a LEM in the ISPS mode is a second generation application of the motor, hence reflects improved progress in motor design and analysis. Only recently have such systems come under close examination for the HSGT application. The active track iron core LSM is being studied in the FRG, the longitudinal flux SLIM is being studied in the U.S. by the DOT. The FRG study should be available in 1977, the DOT study in 1978. Evaluation of the status of these systems must await these reports.

In the FRG, a small scale (2.5 t, 5 m long) low speed (30 km/hr) demonstration vehicle has been shown by Thyssen Henschel in Kassel, and a small scale model has been demonstrated at the University of Braunschweig, both utilizing the active track iron core LSM. Use of the SLIM at low speeds has previously been demonstrated by Rohr Corporation in the U.S.

There are three major aspects to be considered in evaluating the potential of a LEM for ISPS application. They are:

- verification of availability of adequate attractive forces
- system costs of ISPS mode
- controllability of the forces.

The present direction of the research is in establishing that adequate suspension forces exist, and defining the overall system cost of designing the LEM under the constraints that adequate lift and guidance be maintained. For example, it is known that the ISPS SLIM pays a high system cost in reactive power, (affecting the PCU size) to integrate suspension into the motor. The purpose of the DOT experiment is to verify the availability of adequate suspension forces and to define the reactive power "cost".

It is also necessary to study control schemes which allow the suspension forces to be decoupled from the propulsion forces. The research at Rohr in the U.S. has addressed this for an ISPS SLIM, work at the University of Braunschweig and Transrapid-EMS in the FRG has addressed this for the iron core LSM.

In addition to these machines, others have been considered. As an example, the "magnetic river" will be discussed.

### 3.3.1 Magnetic River

The "magnetic river" concept has been promoted by Professor Laithwaite at the Imperial College in London for ISPS operation. It is essentially a transverse flux LIM operating in the high slip mode. Since the LIM develops large repulsion forces at such slips it can be used for suspension as well as propulsion. Critics of this scheme point out that the motor efficiency  $\eta$  is given approximately by the relationship

$$\eta = (1 - \text{slip})$$

hence at high slips the efficiency is inherently low. For this reason

it does not appear that development of this scheme is practical at the high power levels that would be required for an HSGT system.

The analysis of the "magnetic river" concept is still in its early stages [9].

### 3.4 Power Collection

The power collector is a critical subsystem for a passive track, high speed system. To date, power collection using pantographs has been demonstrated at low speeds, and it is anticipated that a multistage pantograph system will allow DC power collection at speeds to 300 km/hr within the next few years.

A long endurance, high speed power collection system has yet to be developed, although research has led to the identification of several promising schemes. Most promising is the brush/rail scheme, but the problem of brush wear in the hostile environment of a HSGT vehicle has yet to be solved. Brief descriptions of examples of research in power collection techniques follow.

#### 3.4.1 Brush/Rail

An experimental study of power collection by sliding contact was undertaken by the AiResearch Manufacturing Company for the DOT in 1971. Using captive contacts in a three rail wayside configuration, satisfactory performance was demonstrated at speeds up to 503 km/hr. The three rail distributor, 457 m long, with a 3.8 m spacing of the support insulators, was designed for three phase (AC) distribution.

Work in the FRG has been carried out by PM and Transrapid-EMS. In the past the EET, shown on page 42, utilized three phase power at 3 kV and 1 kA for propulsion via DLIM. This power

was collected by a brush carriage from three current rails. The brush carriage is guided by air cushions and pulled forward by a tow arm fixed to the EET body, substantially decoupling the collector from the vehicle body dynamics. The current rails were provided with exchangeable contact surface plates to study power rail erosion. Results with copper plates were good, whereas results with aluminum alloys were seen to vary with the specific brush material used.

The primary outstanding problem for the brush/rail type of power collector is that of brush wear. Further investigation of this problem will require long duration testing under actual field conditions.

#### 3.4.2 Electric Arc

Power collection via electric arc is a noncontacting scheme. Although some limited work has been carried out, this approach must be considered speculative at this time. The potential of this scheme hinges on reducing electrode wear to an acceptable level by keeping the arc in constant motion. The electrode wear on the wayside power rail should be low due to the high vehicle speeds involved, but the wear of the onboard electrode presents an additional problem. Techniques for reducing onboard electrode wear are being investigated [10].

The electrode wear problem is difficult, if not impossible, to handle analytically, and a significant development effort will be required to provide the empirical data necessary to evaluate feasibility for HSGT applications.

Additional problems such as that of suppressing arc extinction by wind gusts, will all require extensive experimental studies and field tests.



#### 4.0 REPULSION MAGLEV

Hardware studies of repulsion maglev systems are just now coming to a scale which allows the evaluation of a system, rather than just components. These hardware efforts are being initiated by the Japanese National Railroad in Japan where a 7 km test track at Miyazaki is being constructed for a 500 km/hr vehicle, and to a lesser degree by PM in the FRG at Erlangen where a 200 km/hr vehicle travels a 280 m circular, banked, test track. The JNR vehicle will be the first and only repulsion maglev vehicle to be completely levitated and propelled with EDS suspension and LSM combined propulsion/guidance. The LSM track winding for the FRG vehicle, now being installed, will be used only for propulsion.

Although conceptual vehicles abound on paper (in the U.S., Canada, FRG, France, Britain), the assumptions used call for extensive verification. There are three major areas in which verification is required; they are:

- a. development of cryogenic hardware
- b. development of LSM
- c. control of vehicle dynamics.

For the most part, the existing conceptual designs rely heavily on speculation in these three areas, hence the extent of validity of these designs is open to question. Due to the extensive impact on system design of these items, it is more important to assess the overall progress towards their solution than to scrutinize the existing conceptual designs on a one by one basis. Sections 4.1 to 4.6 will therefore address the progress of worldwide research in these critical areas, rather than compare or evaluate various conceptual designs. There is too much uncertainty in overall designs to allow detailed comparisons. This is an important point, and it also precludes comparison

between EMS and EDS systems somewhat, because EDS hardware designs (EDS + LSM) have not yet been validated to the degree EMS systems (EMS + LIM) have.

#### 4.1 Suspension System

Suspension for the vehicle is obtained by means of the repulsion force induced on onboard SCMs as they are propelled along a conducting guideway. This is termed the EDS suspension; schemes investigated to date fall into three categories

- normal flux (uses a single magnet)
- null flux (uses two magnets, one on each side of the track)
- difference flux (uses a null flux track loop connection)

Either sheet or coil tracks can be used for the normal and null flux configurations, but the difference flux configuration requires an inverse pair arrangement of track loops or vehicle coils. The difference flux scheme is a type of null flux configuration, the distinction is emphasized herein because the analysis, performance and hardware implementation of these two schemes is somewhat distinct.

Although the normal flux configuration is easier to implement in the hardware sense, null flux and difference flux methods gained attention due to their promise of decreased magnetic drag. Analysis has confirmed that the null flux and difference flux systems do offer reduced drag, but has also identified the following tradeoffs compared to the normal flux system;

- a. For both null and difference flux schemes the SCM excitation currents must be higher, hence the magnet design is complicated and the size and weight of each SCM coil increases. (In addition to the larger coil cross section required, internal coil forces rise with the square of the operating MMF (amp-turns), requiring additional mechanical support.)
- b. Twice as many onboard SCMs are required for the null flux scheme. Twice the number of track coils are required for the difference flux system. This presents a vehicle/guideway hardware tradeoff.

- c. The suspension system stiffness is characteristically higher, which can be either advantageous or not, depending on the circumstances.

In general it is necessary to operate the null and difference flux systems about a zero bias to take practical advantage of the reduced drag. This is most compatible with the lateral guidance function, rather than vertical lift, since the lift system must supply the large bias of the gravity load. This has apparently led to the recent emphasis (1975-1977) on "hybrid" systems utilizing normal flux for lift and difference flux for guidance.

As regards choosing one configuration over another, each system has its own characteristic advantages and disadvantages. The important point is to be familiar with the status of the existing knowledge about each system so that valid comparisons can be made for a specific conceptual design and application. The theory for all these configurations is well advanced, as will be discussed in the following sections. Further development of the cryogenic hardware, however, will be required before clear cut choices can be made for a specific application.

Specific performance comparisons and selections between these three systems (normal, null, difference) are frequently made, but such comparisons must be critically examined. One must keep the tradeoffs in mind. There is a basic vehicle/track tradeoff between the:

- installed cost of track conductor, and the
- cost of the onboard SCMs and associated cryogenics.

This tradeoff involves the complete system, which cannot be defined without knowing the specific application. For example, the decision as to whether or not it is cost effective to increase the onboard SCM costs to decrease the guideway conductor costs will depend on the number of vehicles, hence the traffic density involved.

Rather than identify choices, parameter studies of various schemes can only be used to define the tradeoffs as best possible. A system can only be chosen when the application (route/traffic density, etc.) is completely defined. Comparisons, frequently made for fixed drag ratio or fixed guideway conductor, are not sufficient since any of the following variables

- coil excitation (superconductor weight)
- track weight (guideway conductor cost)
- coil topology (cryostat hardware problems)
- clearance (safety/reliability)

can be used to vary the following performance parameters

- lift
- drag
- overall cryogenic requirements

In general, comparisons between systems based on a given lift to drag ratio will yield different coil excitations and track weights, and merely define a SCM hardware/track cost tradeoff; but these comparisons do not explicitly identify a choice. Clear-cut decisions are difficult to make unless the performance costs of the complete system can be clearly defined. Therefore, the intent of the following sections will not be to compare these systems, but to address the extent of validation of the analytical models used in the design of a conceptual system.

#### 4.1.1 Normal Flux

Suspension forces for a normal flux maglev configuration are obtained as the onboard SCMs traverse a conducting guideway and repulsion forces are set up by the induced eddy currents. The guideway conductor can be either a continuous sheet, a ladder, or an array of coils. Numerous normal flux SCM/ track geometries have been studied, but

they can be divided into three major categories, depending on the track configuration. These are the

- single track
- corner guideway
- double track (split guideway)

In the single track system the vehicle coil traverses a flat guideway conductor. Only the normal force is useful for suspension, since the transverse force (due to the finite guideway width) is destabilizing. The usual arrangement consists of 2 rows of vehicle coils, one on each side of the vehicle, and two parallel guideway conductors, one under each side of the vehicle. This scheme, used to provide lift only, is being developed in Canada, the FRG, and Japan. The Canadian Institute of Guided Ground Transport and the PM are studying the sheet track case, whereas JNR is studying the coil track case. This single track configuration has been extensively investigated, both analytically and experimentally, and is well understood [11-13].

A scheme for obtaining both lift and guidance from a single SCM is the use of a corner, or "L shaped" guideway surface. This scheme has been investigated both analytically and experimentally by Ford, where a hat-shaped guideway provides corners at each side of the vehicle for lift and guidance [14]. Although development of this scheme ended in January 1975 with the termination of the Ford work, it was shown to be a feasible option.

The double track, or "split guideway", consists of two guideway tracks for each vehicle coil. The guideway tracks are parallel, with their line of separation running under the centerline of the vehicle coil in the longitudinal direction. This guideway provides a stabilizing lateral force, in contrast to the single track guideway, hence it can be

used for both lift and guidance. This scheme has been investigated in the US at MIT ("Magneplane") [15], and in England at the University of Warwick (Wolfson Project) [16] in small scale hardware studies, and in Canada at the CIGGT [17] in a conceptual design study.

The magneplane variation uses a split trough-shaped guideway with a single row of large saddle-shaped SCMs along the underside of the vehicle body. The University of Warwick design uses two parallel flat tracks and a flat vehicle coil.

In contrast to the MIT and University of Warwick designs, the CIGGT did not study this configuration for primary means of suspension, but analyzed it as a backup means of obtaining additional guidance. In the CIGGT design, the lift tracks are under the two sides of the vehicle, and the LSM propulsion coils are under the center of the vehicle. For large lateral displacements the LSM coils react against the lift tracks to provide guidance forces in a manner analogous to the split guideway case.

#### 4.1.2 Null Flux

Null flux schemes are not being actively pursued at this time for lift, although they have been vigorously investigated from an analytical and experimental standpoint [11-12]. Experimental work has been done at Siemens on a rotating wheel (for sheet tracks) [13], and in Japan [18].

For the purposes of evaluating conceptual designs, the existing electromagnetic models can be considered validated. The decision as to whether or not the increase in SCM complexity associated with null flux schemes is cost effective for the drag power savings must depend on overall system considerations, hence is application specific. At this time, it appears that the necessary doubling of onboard SCM requirements will offset the gain in lowering the drag power.

#### 4.1.3 Difference Flux

Difference flux schemes have recently received wide attention. They are now being applied to the problem of lateral guidance [17,19].

In the early 1970's JNR conducted considerable research into using a difference flux scheme for lifting purposes. This research consisted of analytical and rotating wheel studies as well as the development of a light weight, low loss cryostat specifically for this application. This cryostat was dubbed the W-1, or wing type cryostat. This development has terminated, as JNR is no longer developing this concept for application to lift.

The CIGGT, Siemens and JNR are now actively considering various difference flux schemes for lateral guidance, making use of the onboard LSM SCMs for combined propulsion/guidance.

In the case of CIGGT, this scheme is considered for application in providing guidance for the flat track. The CIGGT feels a flat track is a necessity due to the winter snow and ice conditions in Canada. The scheme, which was proposed by Atherton and Eastham at the CIGGT in 1974, uses passive figure 8 loops placed in the guideway (on top of the active LSM propulsion winding). The guidance forces are obtained by a difference flux interaction between the LSM SCMs and the figure 8 loops. This scheme has now drawn the attention of the EDS group at Siemens, in the FRG. The analytical and experimental work done by CIGGT is now being picked up at Siemens, where additional analytical work has been done, and rotating wheel experiments are planned for 1977.

In MITRE's opinion, the state of analytical work, with some experimental support, is adequate to show that reasonable guidance forces can be generated. However, the analyses conducted to date have not fully considered the overall vehicle dynamics. It will be

necessary to conduct additional vehicle dynamical modeling and experiments to confirm the potential and safety of the flat track configuration.

JNR is investigating another type of difference flux configuration, one which makes use of a difference flux connection between the LSM track windings [20]. Its investigation is being pursued on the inverted-T track at Miyasaki. In this scheme the LSM is divided into 2 parallel machines, one along each side of the vehicle. Whereas the CIGGT and Siemens designs use track loops (figure 8 loops) in addition to an LSM winding for the generation of guidance forces, the JNR design connects the two LSM windings into a difference flux configuration, providing guidance forces without requiring additional track loops. The results of the tests at the Miyazaki test track will be a valuable means for evaluating this scheme.

This recent trend towards integrating propulsion and guidance appears promising for two reasons:

- lower magnetic drag power
- simpler overall vehicle/guideway design

The difference flux lateral guidance scheme reduces the magnetic drag power compared to a normal flux configuration. The integration of propulsion and guidance allows both forces to be developed on the same guideway surface, simplifying the vehicle as well as the guideway.

#### 4.1.4 Sheet Track vs. Coil Track

The conducting track for normal or null flux schemes may be implemented using either a sheet, a ladder, or a linear array of coils. There is still some uncertainty as to which is preferable, but this is not a vital issue for EDS systems, as the replacement of one track by the other is relatively easy--only minor guideway modifications would need to be done. The proponents of the coil track feel it has the advantage of greater design



flexibility, since there are more parameters to vary. The critics of the coil track think no overall improvement can be realized by varying these parameters.

For the purpose of an assessment, either of the schemes will work, and all are compatible with essentially identical vehicle and guideway topology. Therefore, the final decision can be postponed pending a final system optimization. For the time being, the more critical issue is that of the topology of the suspension configuration chosen, as both the vehicle and guideway design are sensitive to it.

An assessment of the performance of each scheme should await the completion of the conceptual design system studies now underway in Japan. For the time being, it is only important to be cognizant of the different options that have been proposed, and the level of analytical and experimental work that has been accomplished.

#### 4.2 Propulsion System

The QFAN has been investigated by Ford as a propulsion option for the EDS system. For near term system implementation, Ford suggested driving the fan with a gas turbine. The state of knowledge for this scheme is well established by the aircraft industry, with the exception that further development of noise suppression techniques are being considered for the HSGT application. At this time, however, only the air core LSM is being actively pursued as a propulsion system for the EDS system. Earlier studies of the LIM fell by the wayside as a result of the basic incompatibility of the small gap necessitated for the LIM compared to the large gap typical for EDS suspension schemes. Both the status of the QFAN and the LSM will be addressed in this section.

#### 4.2.1 QFAN

Ford issued a subcontract to Hamilton Standard to address the issues of noise and pollution for a QFAN. The result of this study indicated that it is likely that a QFAN driven EDS vehicle will be noisier than an LSM driven vehicle, but the aerodynamic noise of the vehicle shell itself moving at high speed is so great that the QFAN noise may not be significant at cruise. Estimates vary from 80-100 dBA (at 15 m) for the bare-body aerodynamic noise whereas predictions for the noise of the QFAN itself (to drive a single 450 kN vehicle at 135 m/s) are 86 dBA (or less with further development).<sup>4</sup> More definitive work, however, is required before conclusions can be drawn as to the overall noise of these HSGT vehicles.

The petroleum fuel powered QFAN has an inherent wayside pollution problem--one envisions the omissions of a stream of aircraft-type engines at short headways constantly polluting the HSGT right of way. The high traffic densities required to justify HSGT systems insure heavy levels of emissions. The overall pollution problem, of course, is subjective in that the fossil fuel/electric propulsion option trades wayside pollution (along the track) for centralized pollution (at the generating plant).

Ford considered a rotary electric motor (REM) driven fan to solve the problems of wayside pollution. (A wayside power collector would be required.) This scheme, however, cannot be considered well developed at this time. Conventional REMs are too bulky and heavy for the power levels required for such a system. In fact, the Ford report ruled them out and used predicted weights for superconducting REMs. Development of lightweight superconducting REMs at the appropriate power level, for a mobile application, would entail a major development effort, as will be discussed in Section 5.1.1.2. In MITRE's opinion, the possible benefits of such a system do not appear to justify such a major development program at this time.

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<sup>4</sup>The noise can be lowered at the cost of motor efficiency.

In any case, advanced propulsion systems are generally promoted for their potential to reduce the negative overall environmental impact of alternative forms of transportation, and the gas turbine has not drawn further attention to date.

#### 4.2.2 LSM

Although the emphasis of this report is on suspension, not propulsion systems, the integration of lateral guidance and propulsion in the LSM makes the propulsion system an integral part of the suspension system. In addition, the considerable size and weight of the propulsion system make it a major part of the overall conceptual design.

At present, several integrated lateral guidance/propulsion systems have been proposed, but only the difference flux method utilizing two parallel LSM vehicle coil arrays and a difference flux LSM track winding connection has been tested on a vehicle. This concept has been studied by JNR since 1973 with rotating wheel tests. It has also been tested on JNR's ML-100A to speeds of 60 km/hr, and will be incorporated in the Miyazaki test vehicle, the ML-500.

The LSM propulsion/guidance system affects the overall vehicle design considerably, since the onboard vehicle SCM configuration and cryogenic requirements as well as the guideway geometry are sensitive to the configuration chosen. In contrast to the EMS system, the EDS system guideway shape is still open to considerable changes. For example, the CIGGT and Siemens are proposing flat topped guideways whereas JNR is studying inverted-tee and U-channel shapes. (All three are using variations of an LSM with a difference flux track winding connection for combined propulsion/guidance.)

Until the propulsion/guidance configuration is more clearly determined, repulsion maglev conceptual designs will reflect a wide degree of variability and speculation.

It is useful to note that the vertical member of the inverted-tee track at Miyazaki was planned to be demountable, so that other guideway and vehicle shapes can be tested. This reflects the variability in guideway configuration that pervades the worldwide research.

In addition, shielding the passengers from the LSM magnetic fields, if found to be necessary, will have strong vehicle design implications, adding more uncertainty to the conceptual designs presented to date. Magnetic shielding is discussed in further detail in Section 5.0, as it is considered more a system problem than a component problem.

At the present time, LSM analysis is at the point where the basic propulsion system tradeoffs are well understood, and confirmed by experiment. These are:

- power factor
- efficiency
- size of track windings
- stage length
- thrust
- excitation frequency

System studies have been completed for single vehicle systems, but apparently none as yet for trained vehicles. System studies of trained vehicles are now underway at JNR.

The electromagnetic properties of such systems have been quite thoroughly investigated, and experimentally verified for cruise

conditions. The critical areas which need further analytical work before the LSM can be considered adequately described for conceptual design purposes are:

- control of the LSM (including vehicle dynamics and performance over faults)
- dynamic (acceleration and braking) performance
- considerations of vehicle motion on LSM performance

Since the LSM consists of a passive vehicle (with an array of SCMs) that are "pulled" along by the traveling wave on the powered track, wayside control of the closed loop response is a critical issue. This work is being pursued in 1977 both by JNR [21] and Siemens [22], and deserves close attention. An aspect of LSM control which MITRE believes needs research involves the LSM performance when the vehicle traverses an electrical fault in the track winding. Siemens has reportedly done an analysis of the transient forces in order to insure safe LSM operation over faults. Experiments have yet to be conducted.

The dynamic performance of the LSM concerning acceleration and braking performance is not well understood at this time. Further research in this area is also called for.

In addition to the above, further work needs to be done concerning the performance (thrust, power factor, etc.) of the LSM as it undergoes heave, roll, pitch, yaw, and sway motions with the vehicle, as this will affect its control. As of this date, insufficient analytical work has been done in this area.

On the whole, the analysis of the LSM has made significant strides during the last few years, with experimental confirmation carried out at the CIGGT, PM and JNR. Much remains to be done, however, primarily in the area of LSM control.

The onboard hardware aspect of the LSM is also critical, since the SCMs require cryostats and a cryogenic supply system. The design of cryostats for the LSM, as well as their incorporation into the vehicle cryogenic design as a whole, cannot be resolved independent of the selection of guideway geometry, since the LSM is now also used for guidance. The design of the LSM requires an understanding of the entire vehicle system. For this reason, the hardware design of the LSM is still evolving, and will continue to do so for the next few years.

#### 4.2.3 Paddlewheel

A proposed ISPS scheme is the "paddlewheel" concept developed at Ford [14]. This scheme does not appear to merit further development, in the opinion of MITRE, for the following reasons:

- it does not have a significant advantage compared to EDS suspension (i.e., it does not reduce the magnetic drag power for the same guideway thickness at a given vehicle lift requirement)
- it will likely require a significant development effort in the area of rotating superconducting machines.

The paddlewheel is an alternative, theoretically workable scheme that would require a major hardware development program. Its primary potential advantage is that, for vehicles with onboard fuel, the gas turbine driven paddlewheel may be more efficient than a gas turbine driven QFAN with EDS suspension. It trades considerable technological complexity for this possible gain in efficiency. The paddlewheel itself requires a prime mover, as does the QFAN, hence requires either a gas turbine or a power collector/REM. If such a REM is used, it will most likely require the development of a superconducting REM. As will be discussed in Section 5.1.1.2, development of a superconducting REM will require a major research effort.

#### 4.3 Cryogenic Hardware Development

The cryogenic hardware has significant impact on the overall design for two reasons. First, the size and weight of the cryogenic equipment is a considerable fraction of the total vehicle weight, since cryogenics are required for the levitation as well as the LSM SCMs. For example, in a JNR conceptual design, there are 16 SCMs (8 for lift, 8 for thrust/guidance). In a CIGGT design, there are 58 SCMs (8 for lift, 50 for thrust/guidance). The variations in design that are required to accommodate significantly different numbers of SCMs, as well as their physical placement, is significant. Second, the method of storing and/or supplying an adequate quantity of liquid helium for these SCMs presents another uncertainty.

The primary challenge for repulsion maglev is cryogenic development, and lies in maintaining LHe in the cryostats. Two approaches are now receiving attention, they are:

- use of a helium refrigerator in a closed cycle system
- use of sealed cryostats

To date, a refrigerator of reasonable size, weight and reliability does not exist for the HSGT application. They are, however, under development. Nevertheless, at this time it appears that an onboard refrigerator is the most likely candidate for a repulsion maglev vehicle in the future.

As an alternative to using a refrigerator, use of a sealed system is being studied. In such a system, the dewar is partly filled with liquid helium and then sealed. As time passes, the heat load raises the temperature and pressure within the dewar. The SCM coils must be derated (oversized) to operate at the nominal design temperature, which will be greater than the boiling point of LHe at 1 atm (4.2 K). In fact, higher critical temperature superconductors than are now readily

available may well be required. Such a system is serviced at a design interval of several hours to a day, determined when the cryostat temperature/pressure reaches the design limit. During servicing the pressurized He gas is withdrawn and the dewar is refilled with LHe. Since such systems tend towards high temperatures (10-15 K) and pressures (20 atm) after only tens of hours of operation under moderate heat loads (3-6 watts), the demonstration of a viable system will involve considerable development of low heat leak SCMs. Any prediction of their performance at this time involves considerable speculation, since the temperature/pressure rise is a strong function of the heat load, and the heat load is difficult to assess by analysis. Heat loads must be verified by actual dewar construction, and are sensitive to the mechanical design of the cryostat. In addition, the temperature and pressure may rise in a vibrating environment, as experienced onboard a vehicle, adding considerable additional uncertainty to speculations on the performance of such systems in the field. For these reasons, the sealed system must be considered a speculative solution at this time.

Thus the feasibility of the EDS system relies on the development of cryogenic hardware, as both the suspension and propulsion systems use cryogenic technology. To date, the most extensive development on SCMs has been done in Japan, where several cryostat designs have been built and tested. In other countries, SCM hardware efforts have been conducted on a much smaller scale.

Simply put, cryostat design must compromise the following conflicting requirements:

- transmit the suspension forces to the vehicle from the superconducting coil with a lightweight structure
- maintain good thermal insulation between the coil and vehicle.



Since strong lightweight structural members required for force transmission tend to be good thermal conductors, creative design techniques are required to design a cryostat under the above constraints. In addition, the cryostat must provide for large internal stresses in the coil itself, as well as between coils in a multicoil cryostat.

The weight of a superconducting coil increases as it is stabilized against quenching, as the stabilization entails imbedding the superconductor in a copper matrix. Increasing the copper increases the stability at the expense of coil weight.

These problems have been primarily tackled in conceptual designs in Canada, and in the U.S. In the FRG and Japan, hardware has been constructed and tested. This cryostat research will now be discussed.

#### 4.3.1 USA

In 1971, small scale experimental SCMs were constructed and tested on a low speed (50 km/hr) test sled at Stanford Research Institute. At Ford Motor Co., conceptual design studies in conjunction with the Magnetics Corporation of America (MCA) were conducted [14]. No full scale cryostats were constructed, however. The primary feature of the Ford design is the use of "folded" G-10 epoxy fiberglass support columns loaded in compression to support the coils. As reported by Ford, Dr. Y. Ishizaki of the University of Tokyo has noticed a "significant" increase in the thermal conduction of G-10 in a "loaded" condition. Further experiments are therefore necessary to determine the suitability of the design.

A second feature of the Ford design is the proposal to use only superinsulation<sup>5</sup> and eliminate the intermediate temperature radiation shield. Designs in Japan, Canada, and the FRG use intermediate temperature radiation shields.

#### 4.3.2 Canada

The CIGGT group constructed an experimental SCM for testing on their rotating wheel facility. This large, heavy cryostat was neither suited nor intended to be a prototype for a vehicle cryostat. For the CIGGT conceptual design, an isochoric (sealed) dewar system has been proposed. In this sealed system, the dewars are partly filled with liquid helium (at atmospheric pressure) and then sealed. The dewar is serviced daily by exchanging the pressurized He gas for LHe. The service interval is chosen to limit the pressure rise to a maximum of 20 atm and the He temperature to a maximum of 10-15 K to allow operation for a 22 hour day. In addition, the development of commercially suitable Nb<sub>3</sub>Sn (or higher T<sub>c</sub>) superconductors is assumed, as they are required to allow operation at this temperature. This is a crucial point for the feasibility of this CIGGT design.

It should be noted that as the feasibility of such designs is quite dependent upon the actual heat load, it is speculative at this time. The CIGGT design assumes a total vehicle heat load of about 50 W at 4.2 K. This heat load is optimistic in light of the large number of SCMs required and the demonstrated state-of-the-art. The sealed system requires a low heat load, otherwise the pressure and temperature would increase beyond design limits. If heat loads cannot be reduced to the anticipated levels, this sealed system may not be feasible.

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<sup>5</sup> Superinsulation is a well known method utilizing a large number of highly reflecting layers to reduce the heat load caused by radiation from the warm (room temperature) surfaces of a cryostat.

The levitation forces within the cryostat are to be transmitted by compressed superinsulation pads. This technique has been demonstrated in other applications.

This conceptual design is significantly beyond today's commercially demonstrated state-of-the-art, and must be considered speculative at this time. The primary uncertainties are in the following areas:

- verification of feasibility of isochoric operation up to 20 atm in a vibratory environment
- mechanical/cryogenic dewar design heat leak assumptions must be verified
- development of suitable higher  $T_c$  superconductors ( $Nb_3Sn$  or  $NbGe$ )

#### 4.3.3 FRG

Siemens has designed and fabricated cryostats for its test vehicle, the EET [22]. A primary feature of their design involves two intermediate copper radiation shields (4.5 K and 50 K). Structural members for transmitting the forces are of the Heim column type. Liquid He is forced from a control chamber through the coil winding. Part of this stream is split off and expanded in two-phase flow for cooling the first (4.5 K) copper shield and the second copper shield (50 K) with gaseous helium. The rest of the LHe stream is conducted to the LHe chamber of the next magnet. No  $LN_2$  is used.

A cooled aluminum ring is used as a shorted secondary to help retard the field decay in an emergency as well as to shield the SCM from A.C. fields caused by vehicle motions.

It should be noted that the forced flow LHe design used at Siemens was necessitated by the configuration of the Erlangen test track. The 230 m diameter circular test track was banked at  $45^\circ$ ; hence some magnets are at different heights above ground than others, and liquid level

problems arise with centrifugal forces as the vehicle speed varies. Forced flow cooling makes the magnets independent of their position so that they can be standardized for fabrication. Forced-flow design is not likely to be used in a revenue vehicle, where a simple LHe bath is judged adequate.<sup>6</sup>

Siemens has constructed eight prototype cryostats, all of identical design, for the EET vehicle. In contrast, the Japanese have constructed cryostats using numerous design techniques.

#### 4.3.4 Japan

The JNR has conducted a vigorous development program for the superconducting coil and cryostat [23-30]. Figure 51 lists the full scale cryostats constructed for JNR to date by various Japanese industrial firms, and compares them to the Siemens cryostat. The significant feature is the wide variety of problems addressed by this research. Several types of superconducting wire (NbTi, NbTiTa, NbTiZr) with a wide range of copper stabilization (copper ratios from 12:1 to 2:1), and operating current densities (25 to 300 A/mm<sup>2</sup>) were investigated. Coils from 1.0 m to 4.0 m long were constructed, and numerous approaches to force transmission structural members were studied. These points of investigation can be placed in perspective as follows:

##### 4.3.4.1 Superconducting Materials

The various superconductors used reflects the development of improved superconducting wires. These materials are now readily available. The copper ratio and current density chosen will ultimately be dictated by a weight/reliability tradeoff to be determined in the field.

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<sup>6</sup> An exception is the magneplane system, which due to the large size of the onboard coil may require the perfection of a supercritical helium circulation system.

COMPANY	SIEMENS	TOSHIBA								HITACHI		MITSUBISHI					
CRYOSTAT		W-1	L-1		L-3		M-1	M-3	"VERTICAL"	"TUBE TYPE"	ML-100	PCM	HCM-a	HCM-b	HCM-c (ML-100A)		HCM-e
COIL ORIENTATION	HORIZONTAL	HORIZONTAL	HORIZONTAL	VERTICAL	HORIZONTAL (2)	VERTICAL (2)	HORIZONTAL	HORIZONTAL	VERTICAL	HORIZONTAL	HORIZONTAL	VERTICAL	VERTICAL	HORIZONTAL	HORIZONTAL	VERTICAL	HORIZONTAL
SUPERCONDUCTOR																	
TYPE	NbTi	NbTi	NbTi	NbTi			NbTi	NbTi		NbTiZr	NbTiZr	NbTiTa	NbTiTa	NbTiTa	NbTi		
CU RATIO	5:1	6.3:1					12:1/2:1			5:1	8.5:1	4.5:1		2.5:1			
FILAMENTS	300 x 50 μm	361 x 50 μm	361	361			8/361	10		397 X 43 μm	271 x 54 μm	305	305	121			
TWIST PITCH (CM)	5									2.26	2.26	3.2	3.2	2			
COIL																	
L x W (M)	1 X .3	1.2 X .4	4 X .4	4 X .6	2 X ?	2 X ?	1.2 X .3	1.2 X .4	1.6 X .5	1.5 X .6	1.55 X .3 (2)	1.55 X .3	1.55 X .5	1.55 X .3	1.5 X .5		1.5 X .5
MMF (KAT)	515	320	250	500			200	320	500	300	250	250	450	250	150	450	250
CURRENT DENSITY (A/mm <sup>2</sup> )	81						25/50			147		135	135	300	130 <sup>2</sup>		
CRYOSTAT																	
MASS (KG)	540	520		1500		1500	625/555 <sup>1</sup>	1200	360	275	1000	185	225	80?, 145? <sup>3</sup>		130	
STORAGE (I)	?			250		?	?		?	?	?	22	?	?		?	
HEAT LOAD																	
WATTS	4	1		5 (CALC.)		6		1.5	<1.5	3.6	9.7	3				7	
BOIL OFF (1/h)							5-8				13.2	3-5		3			1-2
COIL SUPPORT	HEIM COLUMN	FRAME	CONCENTRICALLY LAYERED STAINLESS STEEL PIPES; STAINLESS WIRES		HEIM COLUMNS		4 METAL COLUMNS		FRP	FRP		CSI	PHI	PHI	PHI		PHI & CSI

<sup>1</sup>WITH ALUMINUM ALLOY OUTER DEWAR WALL  
(748/675 WITH STAINLESS).

<sup>2</sup>ORIGINALLY DESIGNED FOR 300 A/mm<sup>2</sup>  
BUT INSTABILITIES WERE ENCOUNTERED.

<sup>3</sup>80 KG REPORTED IN ADVANCE LITERATURE  
145 KG REPORTED VERBALLY

FIGURE 51  
CRYOSTATS FOR SUPERCONDUCTING COILS

#### 4.3.4.2 Coil Lengths from 1.0 m to 4.0 m

The structural problems of coils vary with their length, hence the study of various length coils is important to develop knowledge of the hardware tradeoffs between length optimums for construction purposes vs. length optimums for performance purposes.

#### 4.3.4.3 Cryostat Configuration

Several configurations have been constructed.

- horizontal and vertical types
- wing type (W-1)
- tube type (coaxial cylinders, "doughnut" shaped)
- L-type
- single coil and multiple coil cryostats

The variety of configurations studied have provided a broad spectrum of cryostat mechanical design experience to the JNR.

#### 4.3.4.4 Force Transmission

Various structural designs have been evaluated for transmitting suspension forces while retaining low thermal losses, these are

- FRP (fiberglass reinforced plastic)
- CSI (compressed superinsulation)
- PHI (plastic honeycomb insulation)
- Heim columns

The evaluation of heat leak at low temperatures for loaded structural members requires an experimental approach. A variety of structural designs have been experimentally investigated.

#### 4.3.4.5 Miscellaneous

Various necessary cryostat features such as persistent switches and removable current leads have also received attention.

Various gaseous He and  $\text{LN}_2$  cooled intermediate temperature radiation shield designs have been studied.

Techniques for developing a cryostat with a mechanical reliability suitable for the HSGT application have been undertaken. In order to reduce the possibility of vacuum leaks developing from welding faults, designs with a minimum number of seams are being considered.

Taken as a whole, this development program is broad in scope, yet further development still needs to be carried out for an optimum cryostat/refrigerator system.

#### 4.4 Refrigerators

If sealed systems do not prove out for the transportation application, an onboard refrigerator will be required. The development of a suitable refrigerator has yet to be demonstrated. For closed cycle systems this is the most critical area of technology remaining to be developed.

According to estimates made at JNR [31] either a refrigerator per cryostat or refrigerator per car scheme can use present technology and keep the weight of the refrigerator to less than 2 tons/car. A Claude or Stirling cycle was found appropriate for 1 ref/car, and a Stirling or Gifford McMahon cycle for 1 ref/cryo.

Although a brief description of the ongoing work will be given in the following sections, the significant point is that a lightweight reliable refrigerator has yet to be demonstrated.

##### 4.4.1 Germany (FRG)

The EET at Siemens can be run for approximately 1 hour of experiments after filling with LHe. A wayside refrigerator is also available. This is a UR80 from Linde that delivers 80 l/hr of LHe or 300 W at 4.5 K.

A 50 m long LHe + GHe pipeline connects the refrigerator to a 2500 l storage vessel, on the ground.

Linde AG is reportedly in the process of developing a lightweight, compact refrigerator for onboard refrigeration. In the meantime, Linde has built an onboard cryogenic supply to provide LHe for the EET magnets. This system is essentially a modified tank system: a small room temperature compressor set generates He gas pressure (2 bar) in a 150 l LHe tank. This gas pressure forces the liquid through the coil windings of the onboard SCMs. During operation of the EET, the helium is vented to the atmosphere. This technique, of course, is not suitable for a revenue vehicle.

#### 4.4.2 Japan

JNR is considering developing an advanced system consisting of an onboard Ne/He closed cycle system using a sealed cryostat with a neon cooled thermal shield. No further information on this is available at this time. Recent information from Japan did, however, disclose work on a condensing heat exchanger and a dry helium compressor.

##### 4.4.2.1 Condensing Heat Exchanger

Sumitomo and Toshiba are jointly developing an onboard refrigeration system - the condensing heat exchanger [32]. This is an integrated refrigerator/cryostat. The refrigerator used is a modified conventional 4 l/hr Claude Cycle helium liquifier with one reciprocating expander and LN<sub>2</sub> precooling. The refrigerator simultaneously provides He coolant to two radiation shields in the cryostat and to the condenser located in the gas phase of the LHe vessel of the cryostat. A 1.55 m X .5 m dummy SCM was located in a 320 kg cryostat. The coil is immersed in 20 l of LHe. Coil support is by means of four folded stainless steel columns and eight wires.



The heat load at 4.5 K is absorbed by the condenser through heat exchange between the GHe coolant from the refrigerator and the evaporated gas in the LHe vessel. The cryostat can be sealed, allowing its temperature and pressure to rise to an equilibrium determined by the heat removed by the heat exchanger coil. This system deserves close attention.

#### 4.4.2.2 Dry Helium Compressor [33]

The compressor is a critical component of a closed cycle refrigeration system, since 27% of refrigeration system failures are caused by mechanical trouble in the compressor and by failure of filters.

A joint effort of the University of Tokyo and the Japan Steel Works has led to the demonstration of a prototype three stage dry helium compressor, for possible application to maglev vehicles. The main purpose of this work was to selectively combine and utilize the technology developed in piston-type compressors. Piston driven machines employing swash plates have already been adopted in high-pressure oil pumps, where their compactness as well as high stability of mechanical balance have been demonstrated. Dry-type compressors may have some disadvantages with respect to the compressor volume and lifetime of piston rings compared to oil-lubricated types; but they are not subject to the problems caused by oil condensation, and they do not require periodic maintenance of the oil separator, as do conventional units.

This compressor has an overall length, width and height of 1.46 m X .4 m X .7 m, respectively. There are 8 reciprocating pistons, four on each side to eliminate thrust force, minimize vibration, and dispense with elaborate foundation support. The pistons are driven by cross heads mounted on a swash plate. The total compression ratio is 1:15 and the maximum delivery and suction pressures are 18 and 3 atm, respectively. The compressor has a flow rate of approximately  $100 \text{ N}\cdot\text{m}^3/\text{hr}$  with a swash plate velocity of 1000 rpm. The compressor, constructed primarily of

ferrous materials, weighs about 1000 kg. At present there are plans to introduce lighter materials to reduce this weight to about 600 kg, however, this will require a specially designed motor. The measured noise, at full load, was 78 and 71 dB(A) at distances of 1 m and 5 m, respectively.

#### 4.5 Sealed Cryostat

A method proposed for maintaining the temperature of an SCM is to use a sealed cryostat. The obvious advantage of this system is that no onboard refrigerator is required.

This concept is being studied at the University of Tokyo and at Tohoku University, in Japan [34]. A simple experiment with a small (10.5 l) cryostat was conducted. With a heat load of .425 W, the LHe temperature rose from an initial temperature and pressure of 4.22 K at 1 atm (for an 81% liquid fill level) to 4.7 K and 1.78 atm after 2.1 hours. Fairly good agreement between theory and experiment were found.

This concept is also attracting attention at the University of Warwick [35] and at the CIGGT [17]. Only analytical studies have been conducted there, however.

#### 4.6 Control of Vehicle Dynamics

The control of vehicle dynamics also has an impact on the overall system, primarily because the vehicle and guideway geometry depend strongly on the system chosen for guidance. Note that this is in contrast to the EMS system, for which either a separate or combined lift/guidance magnet configuration is compatible with similar double beam guideway construction and similar vehicle configurations.

Another area of vehicle dynamics also has considerable importance, although its impact on the system hardware design is not as great. This is the area of damping of the vehicle suspension oscillations. The

EDS suspension has very low inherent damping, too low for acceptable ride quality [36]. Additional means for damping must be provided. This remains an important, outstanding problem for EDS systems. Calculations and experiments by several investigators have shown that the intrinsic damping of the EDS suspension is quite small, too small for acceptable ride quality. Several solutions to this problem have been studied, and appear feasible, but no EDS vehicle has been operated under realistic operating conditions to date. The hardware used in a solution to this problem still needs to be demonstrated on a prototype vehicle.

#### 4.6.1 USA

After early work indicated passive eddy current damping using fixed damping plates or coils would be inadequate, active damping was studied by Ford [17]. In this scheme, a normal coil is placed under the SCM and excited by a control system. The control system consists of an electronic power controller operating according to a control system using motion sensors (i.e., accelerometers). Initial calculations by Ford indicate good potential for this scheme. Further research, however, is desirable to prove out this concept in the field. Although the analysis is well advanced, practical hardware designs have not been thoroughly tested in the field.

An additional scheme has been proposed by Dr. J. Harding, formerly of the U.S. DOT. This is a modified passive damping scheme where passive damping plates (or coils) are suspended from the SCM on a secondary suspension in an attempt to couple more energy from the field than when the damping plate is fixed to the vehicle. This scheme has not yet been analyzed.

Additional work on damping has been done at MIT for the magneplane system, where the LSMs are used to damp heave oscillations via the closed loop control system.

#### 4.6.2 Canada

Secondary suspension schemes to provide damping are only possible if the natural frequency of the SCM suspension is high, allowing the passenger cabin to be decoupled from the primary suspension. The CIGGT has thus proposed a scheme as follows: the levitation magnets are independently sprung from the passenger cabin on a soft secondary suspension. The gravitational load stored in the spring of this secondary suspension allows the SCM to have a high natural frequency as a primary suspension while the passenger cabin rides on the soft secondary suspension. The secondary suspension, hydraulically controlled, provides damping for the magnets.

This scheme must be proven in the field before it can be considered feasible. Two problem areas which need to be addressed concern the increased vibration load that the high primary suspension frequency will introduce to the SCMs. These are:

- effect on cryostat reliability
- increased LHe boiloff

The vibration level of the primary suspension increases rapidly with natural frequency, depending on the spectral distribution of guideway irregularity wavelengths. The CIGGT design has a natural frequency of about 10 cps, which could cause vibrations significantly above the level associated with that of the more conventional EDS suspension with a natural frequency in the .5-1 cps range.

#### 4.6.3 Japan

At last report, JNR is still studying passive techniques for damping, and will proceed to active damping if found to be necessary.

#### 4.6.4 FRG

Siemens has adopted the Ford approach of active damping using active control coils.

## 5.0 TLV SYSTEM COMPARISON

In general, the analytical models, experiments and hardware technology are well advanced for the following suspension components:

- EDS - normal flux, null flux, and difference flux suspension, excluding the means of LHe supply to cryostat (which is not well advanced)
- EMS - separate L/G, combined L/G (transverse flux type)
- AIR CUSHION - static air cushion.

The following propulsion components are also well understood:

- FLUID - gas turbine, except for further development of noise suppression
- LEM - SLIM and DLIM, except for further optimization via liquid cooling of LEM and PCU.

For these systems reliable, accurate conceptual designs can be constructed.

Conspicuously absent from this list is air core LSM propulsion, which is critical for propelling the EDS suspension system. The primary reasons for its absence are as follows:

- complete design of hardware for active track has not yet been demonstrated, though it will be at Miyasaki
- closed loop control of LSM including effects due to vehicle motion has not been demonstrated
- method of LHe supply to cryostats is not yet developed.

In summary, the missing technological links for a valid suspension system design lie in the following areas:

- EDS - development of refrigerator or sealed cryostat for LHe supply to cryostat
- AIR CUSHION - ram air cushion - basic analysis and verification.

The important unknowns for LEM propulsion systems concern the following areas:

- REPULSION MAGLEV - LSM control, hardware, active track costs, development of LHe supply for cryostat
- ATTRACTION MAGLEV/AIR CUSHION - improvements in onboard inverter design, development of DC distribution for passive track machines using LIM propulsion, costs of active track for iron core LSM propulsion.

In light of the uncertainties in several critical areas it is impossible to make completely reliable conceptual designs for valid comparisons of all the candidate systems. Even if it were possible, overall system comparisons are difficult to make, as each system has characteristic advantages to be weighed against its relative disadvantages. For a system with the overall complexity of a HSGT system, absolute comparisons are always difficult to make. What is important, however, is the reliability and accuracy of the analytical models used for predictions of performance and cost based on conceptual designs. If such predictions can be reliably made, a single choice will most likely present itself if the application is completely defined. Some of the major questions to be answered for a specific application are as follows:

- energy requirements
- tracking ability
- safety
- switching
- speed

Brief comparisons based on these points will be addressed in the following sections.

## 5.1 Energy

There are two aspects to the energy question:

- type of energy (onboard fuel or electric)
- energy delivery system (power distribution and conversion)

### 5.1.1 Type of Energy

#### 5.1.1.1 Onboard Fuel

A gas turbine with a noise suppressed, ducted fan is the obvious choice if onboard fuels are allowed. Such a propulsion device is simple, well understood, and compatible with all air cushion and maglev suspensions. The only outstanding technical problem is that of further reducing the noise levels. The political/technical climate at this time, however, is leaning strongly against onboard fuel systems for reasons of wayside pollution and anticipation of a limited petroleum supply in the future. In any case certain suspension types will require a higher fuel consumption than others.

All suspension systems are compatible with gas turbine propulsion, and they can be ranked with respect to fuel consumption in two major groups as follows:

- a. Attraction Maglev (EMS) and Ram Air Cushion (TRACV)
- b. Repulsion Maglev (EDS) and Static Air Cushion.

The first group's power requirement is dominated by aerodynamic cruise drag on the body (about 4 MW for a 30 m long vehicle at 500 km/hr), the second group has a substantial additional power (15-30 kw/ton) required for the suspension system. The EDS system has a magnetic drag, the hinged lip plenum static air cushion has captation drag. The magnetic drag power for the EDS system is essentially independent of speed, while the drag for the static air cushion increases with speed. In addition, the magnetic drag for the EDS system is always

overcome by the propulsion system, while the static air cushion requires compressor power as well as additional power from the propulsion system at high speeds (to overcome captation drag). Therefore, although the power levels themselves can be directly compared, the system consequences are unique for each system.

The overall size of the propulsion system depends on several factors which relate not only to the suspension system, but also to the specific vehicle operational characteristics.

- overall vehicle weight
- starting acceleration
- power reserve for grades, headwinds
- specific aerodynamic design

hence the overall energy usage cannot be more closely compared on a general basis.

Comparisons as to the lower relative energy use for gas turbine vs. electric propulsion systems have been made in the literature, but have limited practical significance, since comparisons merely of energy consumed between gas turbine and all electric systems only represent a small portion of the total system tradeoff. Such a tradeoff also involves aspects of electric distribution and pollution.

#### 5.1.1.2 Electric

Electric systems are currently of greater interest for future HSGT systems than gas turbines. The two major types of electric systems use either passive or active track distribution. It should be noted that it is not clear that an active track system can be all-electric, since some power for air conditioning, lights, etc. will be required in addition to the propulsion power (coupled electro-magnetically) from the track. A small supplementary gas



turbine, as is now used on aircraft, may be required, although other options are being considered.

Systems compatible with the passive track/electric power collector approach can use a linear or a rotary electric motor. The REM would be used to drive a QFAN. Compatibility is based on the size of the suspension gap; those compatible with the LEM are the:

- EMS maglev, static air cushion (LEM compatible)

while those compatible with the REM are:

- EMS and EDS maglev, static and ram air cushion (REM compatible)

For practical purposes, only the EMS maglev and static air cushion systems are compatible with small gap linear electric motors (LSM or LIM). Large gap systems (i.e., EDS maglev and the TRACV) are basically incompatible with a small gap propulsion device.

In terms of power consumption for LEM compatible suspension, there is a clear and significant advantage of the EMS maglev compared to the static air cushion.

For an all electric power pickup system, the large gap suspensions such as the EDS maglev and TRACV systems require a REM driven ducted fan. However, the feasibility of onboard REMs has not yet been demonstrated, primarily because conventional REMs at the power level required for a 500 km/hr vehicle are prohibitive on the basis of weight. Although there has been speculation that lightweight superconducting REMs will someday be available, a significant development program would be required. At the present time research on superconducting REMs is primarily concerned with much larger machines than would be required for a HSGT vehicle. For this reason REM driven vehicles are too speculative to consider at this time.

In addition, it is not certain that an overall weight savings could actually be realized at REM power levels of only 5-10 MVA.

In conclusion, an EMS maglev suspension appears at this time to be the most energy efficient of the feasible passive track / all electric systems.

#### 5.1.2 Energy Delivery System

The energy delivery system is also of considerable interest for various electric propulsion systems, from both a cost and performance standpoint. The electric power distribution system required by the numerous vehicle types varies considerably, depending on whether a passive or active track is employed, and may well play a significant role in the choice between candidate systems. The major factors of interest are:

- installation and operating cost
- power conversion requirements
- traffic density
- number of vehicles per block.

The issue of installation and operating cost and maintenance for active track power distribution versus a mechanical power collection system (i.e., brush/rail) is far from resolved. It has not yet been shown which scheme is less costly, or preferable in the long run. The comparison is further complicated in that passive track LEM propelled vehicles will most likely utilize DC distribution while the active track vehicles will use AC distribution.

The differences in the means required for propulsion power control are also significant, since passive track LEM machines require an onboard power inverter, while the active track LSMs (air core, iron core) require closed loop wayside power control. Onboard systems have high onboard weight, while wayside systems have the technical complexity of vehicle/substation closed loop control and problems controlling two or more vehicles on an active block. Since the costs also depend on the traffic density, high density will favor a wayside PCU, lower traffic densities favor onboard PCU.

The number of vehicles per block is also significant, since this can greatly affect the power distribution system. In addition to the required power level to be distributed to a given section of track, the type of PCU to handle this power level is affected. For example, EDS LSM designs using one or two vehicles per block can utilize a high excitation frequency from an inverter and obtain a short pole pitch for the LSM. This compares to the designs in Canada and the FRG. On the other hand, a design using 10 vehicles/block requires a level of power so large that only a cycloconverter would be feasible for power conversion. This limits the excitation frequency to about 15 Hz, and requires a long pole pitch for their LSM design. This compares to the JNR design.

In summary, the power distribution/conversion problem is a major system consideration, and may well play a significant role in the final choice between candidate systems for a specific application. As the scope of the power requirements depends heavily on the passenger traffic density and speed, further system definitions will be required before the power requirements can be adequately defined. In addition to obtaining more clearly defined system requirements, there are still outstanding questions of critical technical importance. For the passive track system these are:

- high speed brush wear of the power collector,
- DC distribution scheme hardware.

Outstanding questions for active systems are:

- high voltage insulation for track imbedded winding,
- closed loop vehicle control.

## 5.2 Tracking Ability

Claims have been made for superior tracking ability of large gap (i.e., EDS) suspensions compared to small gap (i.e., EMS) suspensions. This has not been shown, for the following reasons:

- The low natural frequency and damping of the EDS suspension may not allow efficient utilization of the large gap.
- The high sprung to unsprung mass ratio for EMS and static air cushion suspensions allow them to make efficient use of the gap.
- The long wavelength nature of the guideway irregularities (10-100 m) involved may not cause a significant additional cost to reduce their amplitude.

The tracking ability depends not only on the gap, but also on the sprung to unsprung mass ratio. As shown in a MITRE report,<sup>37</sup> the gap is the most important factor, since an increase in mass ratio of 1000 could be needed to offset the decrease in tracking caused by a decrease in gap of 10. For this reason, the EDS suspension may eventually demonstrate the ability to track rougher guideways. At present, however, the Miyazaki test track, utilizing the most advanced EDS test vehicle to date, is being constructed to very tight tolerances in order to provide a low level of guideway excitation for the test vehicle. Neither an EMS or EDS system has yet been demonstrated on anything other than a "smooth" test type track.

A problem inherent to EDS systems is the relative difficulty in actively controlling the suspension, because the large gap would require large control power. Control is only feasible for damping, as any

major change in the natural frequency of the suspension is difficult to achieve. The problem arises from the low natural frequency of the EDS suspension, about .5 to .75 Hz. These soft suspensions tend to be gap limited, rather than acceleration limited (i.e., soft (EDS) suspensions allow large gap variations while having low accelerations, while stiff (EMS) suspensions have small gap variations while requiring high accelerations). An additional problem for EDS suspension is that the low natural frequency is a disadvantage for curves and grades.

In conclusion, it has not been demonstrated that one system can utilize lower cost guideway construction techniques.

### 5.3 Safety

It is difficult, if not impossible, to assess the relative safety of either air cushion or maglev suspensions at this early stage of system development. There has been, however, a question about the safety of the EMS maglev system raised by some of the promoters of the EDS maglev system. The argument is basically that the EDS suspension is an inherently stable suspension, and is safer than the inherently unstable EMS suspension. In the opinion of MITRE, this is not a valid indicator of relative safety. There are two faults to this argument:

- The EDS suspension has not yet been shown to have adequate dynamic stability without an additional suspension element, due to its low inherent damping and coupled vehicle modes. In fact, the most likely solutions at present involve an auxiliary, active suspension either electrical (control coils) or hydraulic (active hydraulic) in nature. If the EDS suspension is indeed shown to require an active control system, it will have a failure mode similar to that of the EMS system, and neither system will have adequate stability without an auxiliary control system.

- Since superconductivity requires cryogenic temperatures, any loss of mechanical integrity of a cryostat (due to vibrations, shock, or defective welds) will cause rapid quenching (loss of superconductivity) of the coils and result in loss of lift. A cryostat requires a vacuum space for heat insulation, and loss of vacuum will cause the LHe to boil and the coil to quench. The EDS system has an inherent problem in the mechanical integrity of the cryogenics. Both systems are inherently unstable; the EMS system requires a control system, the EDS system requires cryostat integrity.

These arguments should be no cause for alarm, however, since an emergency landing system will always be available. Successful testing of skids has been demonstrated on the KOMET test sled (EMS system) at speeds to 400 km/hr.

#### 5.3.1 Magnetic Fields

A question of safety worth more attention at this time concerns that of magnetic fields. Only the EDS system, especially when an LSM is used for propulsion, can expose the passengers to magnetic fields significantly above that of the earth's magnetic field. The earth's field is less than .5 gauss. Magnetic fields of the order of 10-100 gauss or so are possible for the EDS and LSM systems. The question of the safety to passengers exposed to such fields is of major concern because there is a possibility that safety will have to be proven before this system can be accepted. There is no reason to believe at this time that magnetic fields at the level found will actually be unsafe, but proving safety can be a complex political/legal/technical issue. As yet, there are no uniform standards to exposure, but workers in permanent magnet plants have their hands regularly exposed to levels above 1000 gauss without any known ill effects.

In practice, it will be difficult to shield passengers to levels below 10 gauss, as the shielding apparatus will be prohibitively cumbersome. The use of superconducting bucking coils within the cryostat as well as iron shields has been investigated by Ford as a means for reducing the fields. Bucking coils are feasible but complicate the cryostat design; iron shields can be extremely massive.

The consequence of the shielding problem is that designs cannot be fully evaluated at this point in time. Whether the vehicle must carry a multiton iron shield or double the amount of superconducting coils to reduce the fields on the passengers is a critical question that is as yet unanswered.

#### 5.4 Switching

Although several active vehicle switching schemes have been proposed to date, all are quite complicated mechanically. It is obvious that any NCS/P vehicle which derives suspension from a guideway with a vertical guideway surface (i.e., inverted tee) will require an elaborate switch. The disadvantage in switching attributed only to DLIMs with vertical reaction rails is true, on inspection, for most vehicles. Any vehicle, suspended from below, which obtains lateral guidance from a vertical guidance surface faces this problem, with or without DLIM. Even though a SLIM appears more suited than a DLIM to switching, it does not alleviate a switching problem that exists due to the suspension itself. This is true for all maglev and air cushion suspensions.

As the need for high speed switching has not yet been demonstrated, it is not clear that this is a critical problem area. In any case, the FRG program now only considers low speed active switches (where the track is moved on the ground). Early attempts to develop an onboard switch using magnets have been unsuccessful, due to the required weight.

To date, the problem of high speed switches must be considered unsolved, and the problem of low speed switching unresolved.

### 5.5 Speed

The operating speed of the NCS/P system appears to be a significant factor in the ultimate choice between the EMS and EDS suspensions. The power required to overcome magnetic drag is constant regardless of speed, posing a considerable disadvantage as speeds decrease well below 500 km/hr. On the other hand, increasing speeds appear to pose a tracking problem for attraction maglev suspensions, due to their small gap, though this has yet to be proven. High speed tests of both maglev systems on guideways of practical construction (i.e., reasonable cost) are still necessary to resolve this issue. Until the guideway construction costs are well understood, this issue will remain open.

All systems, maglev and air cushion, appear ultimately capable of reliable tracking at high speeds, with higher speeds appearing to favor the large gap (EDS or ram air cushion) suspensions, and lower speeds favoring the small gap (EMS or static air cushion) suspensions.

### 5.6 Propulsion System Compatibility

For designs where the primary (noncontacting) suspension is independently sprung from the vehicle cabin, the use of a LEM has an additional hardware problem--it requires its own suspension system. This problem has been handled in various manners for air cushion vehicles, as follows:

- a. TLRV - the DLIM is guided both vertically and laterally by air cushions along the reaction rail (tested to speeds of 100 km/hr). A "thrust link" connected the DLIM to the vehicle.
- b. PTACV - The DLIM, supported by linear bearings, has freedom of motion only in the lateral direction. It is guided laterally by aluminum pinch wheels which follow the reaction rail (tested to 250 km/hr).



- c. RTV-31 - The SLIM gap was allowed to make large excursions, without an independent suspension. THL was planning to use a servohydraulic system for active control of the gap, but this was never implemented.

It is an advantage, of course, if the LEM can be mounted to the chassis of a tight tracking primary suspension, as is the case of an EMS suspension with the suspension magnets rigidly attached to a primary chassis. This has been demonstrated by MBB (Magnetmobile, and KOMET), KM (TR02, TR04, and TU02), MOT (EML-50) and JAL (HSST-01).

Whether the LEM can be attached to the primary suspension for the case where the primary suspension magnets are independently sprung is not known. JAL, however, has proposed such a configuration using independently sprung modules containing both the SLIM and DC suspension magnets.

This is not a problem for a ISPS vehicle, since the primary magnetic suspension as well as propulsion is taken care of by the independently sprung LEM.

Although not a critical issue, the development of an independent LEM suspension system is necessarily an integral part of the vehicle for the following systems:

- conventional air cushion
- KOMET M type EMS Suspension (independently sprung primary suspension magnets).

## 6.0 LOWER SPEED SYSTEMS

The purpose of this section is to point out the major differences between low and high speed systems components. Such systems have the potential to reduce pollution and vibration problems compared with alternative low speed systems.

### 6.1 Maglev

At this time, there is no development program for low speed EDS transportation vehicles. This is a result of at least the fact that the magnetic drag power of such a system would be prohibitive, and the level of technology involved for the benefit itself would appear to prohibit its consideration. EDS levitation derives lift from the repulsive forces generated by the eddy currents induced in the guideway conductor. The eddy currents dissipate an  $I^2R$  loss that is essentially independent of speed (for constant lift). This loss is in the neighborhood of 15-30 kW/ton of lift; a 50 ton vehicle could develop 1 MW in drag power at all speeds. (This loss manifests itself as a drag for the propulsion system to overcome.) For cruise speeds below 150 km/hr, the magnetic drag will overwhelm the aerodynamic drag. At higher speeds, the aerodynamic drag power increases rapidly (as the cube of velocity) until at 500 km/hr the magnetic drag power can be less than half the aerodynamic drag power. From an energy consumption standpoint, the cruise speed for an EDS suspension can be raised to 150-200 km/hr with roughly the same size propulsion motor and power that would be required to operate it at lower speeds. It does not make sense to operate it at lower speeds, since only a marginal increase in propulsion power can increase the vehicle speed to 200 km/hr. Higher speeds are nearly "free" for the EDS system. For these reasons the EDS suspension has no potential as a low speed guided ground transportation system, in MITRE's opinion.

On the other hand, attraction maglev systems (EMS and ISPS) are technically compatible with a low speed application. Little change in

the design of these systems would be required. Perhaps smaller gaps, with lower levitation powers, could be realized than required for the high speed case, but this is not a major consideration. Of greater significance is the reduction in power level for the propulsion system power inverter. The onboard weight and cost of the power inverter decreases rapidly as speed decreases due to the reduction in aerodynamic drag. There is a limit, however, since although the aerodynamic drag power decreases with the cube of velocity, the power inverter size becomes acceleration power limited, not cruise power limited. The speed below which the inverter size remains substantially the same depends on the desired acceleration profile and vehicle weight. For example, the cruise power requirements of similarly shaped vehicles does not vary significantly. However, a heavy (50 ton) vehicle, requiring a .1 g acceleration up to 200 km/hr will require on the order of 2.8 MW from the inverter during the short acceleration phase and might well be acceleration power limited. On the other hand, a light (25 ton) vehicle would only require half that amount and might be cruise power limited. Lowering the speed further would reduce the onboard PCU weight for the light vehicle, but not for the heavy vehicle.

An additional benefit for low speed attraction maglev systems is that low power transistor inverters are now available, greatly improving the inverter specific weight (kg/kW) compared to thyristor inverters.

The fact that lowering the speed improves attraction maglev systems applies equally well for EMS and ISPS concepts.

## 6.2 Air Cushion

Although the static air cushion can operate at low speeds, the power required for levitation can be high, hence this scheme has disadvantages in terms of energy consumption for low speed operation.

Several low speed air cushion systems have been demonstrated and promoted. One of the more interesting is the Otis TTI (75 km/hr) design. This vehicle utilizes a plenum chamber air cushion of the flexible diaphragm type. The essential difference between this design and a high speed design is that it has a much smaller airgap. The high speed design (hinged plate plenum) characteristically has an airgap of 2-3 mm, whereas the flexible diaphragm has an airgap of only a few hundredths of this. The flexible diaphragm type, therefore, can have a significantly lower suspension power.

The ram air cushion suspension, a high speed concept, is not intended for a low speed application.

## 7.0 SUMMARY

The first chapter presented an overview of the worldwide level of hardware research programs for noncontacting suspensions for guided ground transportation systems. The second chapter presented an evaluation, expressing the opinion of MITRE/METREK, of the overall technical progress, both analytical and experimental, of the research.

The primary objective of the second chapter was to briefly provide the reader with an evaluation of the status of this research. The "evaluation" was conducted in the sense of providing the opinion of MITRE/METREK as to the level of validation that can be assigned to proposed conceptual vehicle hardware designs. To this end, the outstanding critical technical issues concerning the various subsystem components, and system as a whole, are presented in a manner so as to emphasize the overall progress towards the solution of critical technical issues. This section presents a summary of the research discussed in the body of this report.

Figure 52 provides a "bar chart" to illustrate the overall progress of NCS/P research. The major categories addressed are:

- suspension only candidates
- integrated suspension/propulsion candidates
- propulsion only candidates

Their state of development is addressed on two levels:

- status of research experiments
- level of validation for revenue vehicle conceptual designs

The "status of research experiments" takes an overall view of the knowledge developed by the various independent research efforts. A few typical references are given. Further details concerning the test hardware is given in the first chapter, the "overview". It should be noted, of course, that the overall progress in several areas is not

CONCEPT		STATUS OF RESEARCH EXPERIMENTS						LEVEL OF VALIDATION FOR REVENUE VEHICLE CONCEPTUAL DESIGNS							
		ANALYSIS		LABORATORY TESTS		VEHICLE TESTS (km/hr)		COMPONENT PERFORMANCE PREDICTIONS		COMPLETE HARDWARE DESIGN		REFERENCES			
		PRELIM.	ADV.	PRELIM.	ADV.	100	200	300	400	PRELIM.	ADVANCED		COMPONENT	AUX. SYSTEMS	
SUSPENSION ONLY	MAGLEV														
	EMS (DC ELECTROMAGNETS)														
	SEPARATE L/G														KOMET M
	INDEP. SPRUNG MAGNETS														KOMET, EML-50
	UNSPRUNG MAGNETS														TR02, TR04, HSST-01, FORD, MIT STUDY
	COMBINED L/G														
	EDS (SUPERCONDUCTING COILS)														
	SEPARATE L/G														
	NORMAL FLUX														
	SHEET TRACK														EET, SRI SLED
	COIL TRACK														ML100, ML100A
	LADDER TRACK														FORD EXP.
	NULL FLUX														
	SHEET TRACK														SIEMENS EXP.
	COIL TRACK														JNR EXP.
	DIFFERENCE FLUX														JNR, CANADIAN EXP
	COMBINED L/G														
	NORMAL FLUX														
	SHEET TRACK														FORD STUDY
	SPLIT TRACK														WOLFSON PROJECT
	NULL FLUX														
	SHEET TRACK														SIEMENS STUDY
	AIR CUSHION														
	CONVENTIONAL (STATIC)														
	PERIPHERAL JET														TLRV, RTV31
	PLENUM CHAMBER														
SIMPLE PLENUM														AEROTRAIN 01	
INTEGRATED SEC. SUSP.														180 AEROTRAIN, PTACV	
DYNAMIC AIR CUSHION															
DYNAMIC FEEDING														02 AEROTRAIN	
RAM AIR														MITRE/TSC STUDY	
INTEGRATED SUSPENSION/PROPULSION	MAGLEV														
	ATTRACTION														
	PASSIVE TRACK														
	SLIM														ROHR CORP., PLANNED DOT STUDY
	LSM (IRON CORE)														
	HOMOPOLAR INDUCTOR														
	ACTIVE TRACK														
	LSM (IRON CORE)														ARGE
	REPULSION														
	PASSIVE TRACK														
	MAGNETIC RIVER														IMPERIAL COLLEGE
	PADDLEWHEEL, etc.														FORD STUDY
	ACTIVE TRACK														
	LSM														ML100A, CIGGT STUDY
	G/P														MAGNEPLANE
	L/G/P														
	AIR CUSHION														MITRE/TSC STUDY
	RAM AIR CUSHION														
PROPULSION ONLY	PASSIVE TRACK														
	LEM														
	SLIM/DLIM														TR02, TR04, TU02, EET, SPAR
	LSM (IRON CORE)														TLRV, PTACV, 144 SUBURBAN
	HOMOPOLAR INDUCTOR														GE STUDY, SIEMENS STUDY
	CLAW POLE														GE STUDY
	AEROPROPELLED														
	GAS TURBINE														180 AEROTRAIN
	SUPERCONDUCTING REM														
	ACTIVE TRACK														
	LEM														
	LSM (AIR CORE)														JNR, FORD, SIEMENS, CIGGT
	LSM (IRON CORE)														ARGE

FIGURE 52  
STATUS OF TLV TECHNOLOGY-1977

equally divided among the programs mentioned. For example, the progress in EMS maglev has been accomplished primarily by the research effort in the FRG.

This chart is not intended to be complete. Other concepts, primarily in the conceptual stage, are not included. It is not felt that more completeness of the table would add to a better understanding of the level of development of such systems as a whole. Suffice it to say that although Figure 52 is not complete, the primary thrust of the research at this time is well represented, and typical examples of some small scale research programs are provided.

The second aspect of Figure 52 deals with the overall "level of validation" that can be ascribed to the existing revenue vehicle conceptual designs. Two aspects of the design are considered separately. They are:

- a. component performance predictions
- b. complete hardware design.

The first concerns the validity of the existing analytical models to predict the performance of a component design. The evaluation is based on whether the extent of data available on tested systems is sufficient to prove the existence of substantially verified analytical models for the prediction of performance of the components. This refers only to the predictions of the forces, etc. of the component itself, not to the status of overall hardware design. For example, in the case of a normal flux, sheet track, EDS magnet; the performance (forces, currents, coil dimensions, lift, drag) is substantially known, independent of the complete development of the cryogenic hardware (cryostat, LHe supply) used to implement it. Even though the hardware is not completely developed, reliable predictions of performance can be made. Hence the category "component performance prediction" refers to the reliability of the analytical or empirical models to predict basic forces as well as

electrical (for maglev) or fluid (for air cushion) requirements. It should be noted that the analysis will not normally be extended to predict all facets of performance; a bar completely across this category indicates a level of confidence that the major aspects of performance are substantially well addressed for the purpose of valid conceptual designs.

The second category, "complete component hardware design" refers to the actual hardware design of both the component under consideration and its auxiliary support systems. For example, an EMS maglev system requires a magnet driver and control system (auxiliary systems). This hardware is well developed; complete component hardware design validity is indicated in the chart.

It should be noted that although the argument could be made that the power electronics for the magnet driver is not completely engineered for reliability in the harsh transportation environment, the technology for the magnet and control system is basically well developed for the purpose of proposing substantially valid conceptual designs. For this reason, the bar indicates full validation for EMS separate L/G and combined L/G suspension hardware.

In contrast to the level of hardware development for air cushion and EMS systems is the EDS system. As noted in Section 2.0 the technique for maintaining the superconducting coil in LHe is not yet fully developed for the HSGT application. For this reason, incomplete validation for the "complete hardware design" is indicated in the Table.

A brief summary of the overall status of maglev and air cushion HSGT systems follows.



## 7.1 Air Cushion

Prototype suspensions for conventional air cushions are well developed. The plenum chamber with integrated pneumatic secondary suspension has been demonstrated on an elevated guideway (in France) at speeds to 430 km/hr with a gas turbine for propulsion. Although this type of suspension has been demonstrated with a DLIM at a speed of 250 km/hr on the PTACV, higher speeds with a LIM might require further development as far as the method for suspending the LIM is concerned. The method used on the TLRV is a good example.

As indicated in Figure 52, conventional air cushions have been well tested and are adequately understood as a vehicle component.

## 7.2 Repulsion Maglev

Although the theory and analysis of the EDS suspension concept is well advanced, much work is still needed for the LSM, primarily in the area of LSM closed loop control considering vehicle dynamics, and in the area of active track design. Work in this area is progressing well in the FRG and in Japan.

The hardware development of EDS systems has made considerable progress in both the FRG and Japan, primarily in Japan. The development of lightweight reliable, low loss (heat leak) cryostats is well underway, though optimization still requires a strong development program.

The primary area requiring intensive development for EDS systems is in the method of supplying LHe to the cryostats. If future work proves that very low loss (1-2 W at 4 K per coil) cryostats can be designed, sealed cryostats may be feasible, though this must be considered speculative at this time. In lieu of sealed cryostats, LHe refrigerators can be used, but their development for the HSGT application will still require a considerable undertaking.

### 7.3 Attraction Maglev

Attraction maglev suspension hardware has been extensively demonstrated. Both EMS and ISPS hardware has been demonstrated in small test vehicles at low speeds. A high speed EMS suspension test has been run at 400 km/hr with the KOMET test sled. In general, the design and performance of existing EMS designs is well understood, while work on the ISPS LEMs is just now undergoing thorough investigation.

Improved hardware and control system configurations are being studied to extend the performance of existing systems. In fact, a joint US/FRG test program is now addressing the issue of coupled vehicle/guideway dynamics.

EMS system development has been quite substantial. The primary outstanding areas for attraction maglev system development concerns DC power distribution and decreasing inverter specific weights, as both of these affect the onboard weight for passive track systems. For active track systems, more extensive system designs still need to be completed for evaluation.

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