Magnetic levitation and MHD propulsion

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Résumé. — Depuis quelques années nous assistons à un redémarrage de programmes concernant la lévitation et la propulsion supraconductrices. Différents systèmes supraconducteurs de lévitation et de propulsion seront décrits en examinant plus particulièrement l'aspect électromagnétique. Quelques programmes à travers le monde seront abordés. Les trains à sustentation magnétique pourraient constituer un nouveau mode de transport terrestre à vitesse élevée (500 km/h) pour le 21^{e} siècle. Les japonais n'ont cessé de s intéresser à ce système avec bobine supraconductrice. Ils envisagent un stade préindustriel avec la construction d'une ligne de 43 km. En 1991 un programme américain pour une durée de six ans a été lancé pour évaluer les performances des systèmes à lévitation pour le transport aux Etats Unis. La MHD (Magnéto-Hydro-Dynamique) présente des avantages intéressants pour la propulsion navale et un regain d'intérêt apparaît à l'heure actuelle. Le japon se situe là encore à la pointe des développements actuels avec en particulier les premiers essais en rade de Kobe de Yamato I, navire de 260 tonnes, entraîné par MHD.

Abstract. — Magnetic levitation and MHD propulsion are now attracting attention in several countries. Different superconducting MagLev and MHD systems will be described concentrating on, above all, the electromagnetic aspect. Some programmes occurring throughout the world will be described. Magnetic levitated trains could be the new high speed transportation system for the 21st century. Intensive studies involving MagLev trains using superconductivity have been carried out in Japan since 1970. The construction of a 43 km long track is to be the next step. In 1991 a six year programme was launched in the United States to evaluate the performances of MagLev systems for transportation. The MHD (MagnetoHydroDynamic) offers some interesting advantages (efficiency, stealth characteristics, ...) for naval propulsion and increasing attention is being paid towards it nowadays. Japan is also up at the top with the tests of Yamato 1, a 260 ton MHD propulsed ship.

1. Magnetic levitated trains.

1.1 INTRODUCTION. — The interest in magnetic levitated trains is difficult to appreciate in France due to the successful French tradition for trains. MagLev vehicles are often compared to low flying aircraft for intermediate distances rather than trains. Two problems become important at high speeds for classical railway trains : energy transmission (trolley arm and wire) and the contact between rail and wheel (supporting, mechanical stresses, guidance and wear). These problems limit the commercial upper speed to 400 km/h even if the TGV has run at 515.3 km/h, May 18. 1990. MagLev vehicles suppressing these two problems are offering a new way forward for transportation, but they have to prove their capacity to transport people at speeds higher or equal to 500 km/h. The problem for the propulsion power remains in all cases at high speeds since the aerodynamic drag power increases as the cube of the speed. The use of low pressure tubes would decrease this propulsion power, but this future aspect is out the area concerned by this article.

The interest in MagLev, in addition to its possibility for travel at high speds, is its lower noise level, absence of track wear, and ride quality. Nevertheless, the aerodynamic noises become dominating at high speeds compared to rolling noises (typically above 300 km/h [1]).

1.2 OPERATING PRINCIPLE. — The idea to use an a.c. excited coil for the levitation and propulsion was first discovered by a French inventor, Bachelet, in 1914, but the first important studies only began in the sixties, particularly in the United States (at MIT) which stopped them in the seventies. Only the Germans and Japanese kept on important programmes up to now, while the United States started their programmes up again in 1990. The magnetic levitation may be electromagnetic or electrodynamic.

The electromagnetic system is based on the attraction between controlled electromagnets and a magnetic track. The gap is small (10 to 15 mm) with conventional magnets and has to be actively controlled with very high reliability. German researchers are working on this system (development of Transrapid vehicles) but as no superconductivity is involved, no further details will be given.

The electrodynamic system is based on the repulsion between electromagnets on board and conducting sheets or short circuited coils on the track. The power dissipated in the track is called magnetic drag and brakes the vehicle. Sheets are less complex but coils reduce the magnetic drag. No control is required, but this natural levitation is only possible above a certain speed, roughly 70 km/h. The clearance may be large (100, 150 mm) if powerful superconducting magnets are used.

Once in levitation, the vehicle has to be guided and propelled. These functions may be accomplished separately or in combination.

For the electrodynamic system, guidance is performed by the interaction between a magnet on board (identical or different to the magnet for levitation) and coils or conductive sheets on the track. The guidance may be assumed for example by zero flux coils as shown in figure 1. No eddy current is induced (no magnetic drag) when the vehicle is at the centre, but as soon as it is no more in this position, currents are induced and they create righting electromagnetic forces. The same coils may be used for propulsion [2]. The vehicle is propelled in both cases

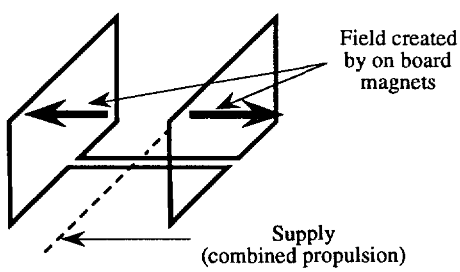

Fig. 1. — Zero flux coil for guidance.

(electromagnetic and electrodynamic systems) by a linear electrical motor. Asynchronous solutions are not suited for electrodynamic systems without magnetic materials and with a large « gap » (low efficiency and power factor). The best solution for the electrodynamic system is the synchronous linear motor with the field winding on board. The multiphase armature windings on the track are supplied by a power converter whose frequency (f) is matched to the speed (V) of the vehicle ($V = 2 f L_p$, L_p . magnet pole pitch). With this active track the power on board is minimal and the problem of energy supply is thus solvéd. The power on board for propulsion is indeed theoretically zero (short circuited superconducting magnets). It is reduced practically to just the thermal losses of the cryostat. The power on board for the helium refrigerator, lighting and air-conditioning may be electromagnetically supplied without contact through the track coils for the levitation and special coils on board using harmonic fields [3]. At low speeds batteries supply the power.

In all cases superconducting coils operate in persistent mode, see for instance the second part of the paper.

1.3 JAPANESE PROGRAM. — The Japanese started their MagLev programme in 1970, and have manufactured eight vehicles from 2 to 20 tons (Tab. I) tested on a 7 km long track. Their studies have always involved the electrodynamic system using a superconducting coil on board [4]. Their ML 500 vehicle is famous due to its world speed record of 517 km/h in 1979. On board helium refrigerators appeared in 1979. The inverted T guideway has been left, in favour of the present U-shaped configuration (Fig. 2). The vehicles MLU 002 (Tab. II) and MLU 002N are close to a commercial version, with a length of 22 m and a weight greater than 17 tons. MLU 002N has replaced MLU 002 which was destroyed by a fire, in 1991, due to the puncture of a tyre.

In 1989 the construction of a new test track was intended to determine the real capacities of MagLev systems in a design, closely ressembling an eventual commercial design. This track, now under construction, would form part of a future link between Tokyo and Osaka. Crossing a mountainous area the tunnels are numerous and have a large cross-section area to avoid aerodynamic pressure problems (aspect ratio of train to tunnel about 0.1). On board the three functions of levitation, guidance and propulsion are accomplished by a single superconducting magnet. On the track, levitation and guidance are assumed by 8 shaped coils (Fig. 3). This geometry suppresses the magnetic drag at low speeds when the vehicle is supported by the wheels : the centre of the 8 shaped coils is on the superconducting winding axis. At higher speeds, when the levitation is achieved, the wheels are retracted and the 8 shaped coils induce large levitation and guidance forces. The magnetic drag is low and the magnetic spring coefficient in the vertical direction is rigid. The three phase armature windings are distributed

Table I. — *MagLev test vehicles developed in Japan.*

Year	Name	Length	Weight	Particularity
1972	LSM 200	4 m	2 tons	asynchronous motor
	ML 100	7 m	3.5 tons	
1975	ML 100A	5 m	3.6 tons	
1977	ML 500	13.5 m	10 tons	World record 517 km/h
1979	ML 500R	12.6 m	12.7 tons	
1980	MLU 001	10 m	10 tons	
1987	MLU 002	22 m	17 tons	
1993	MLU 002N	22 m	20 tons	

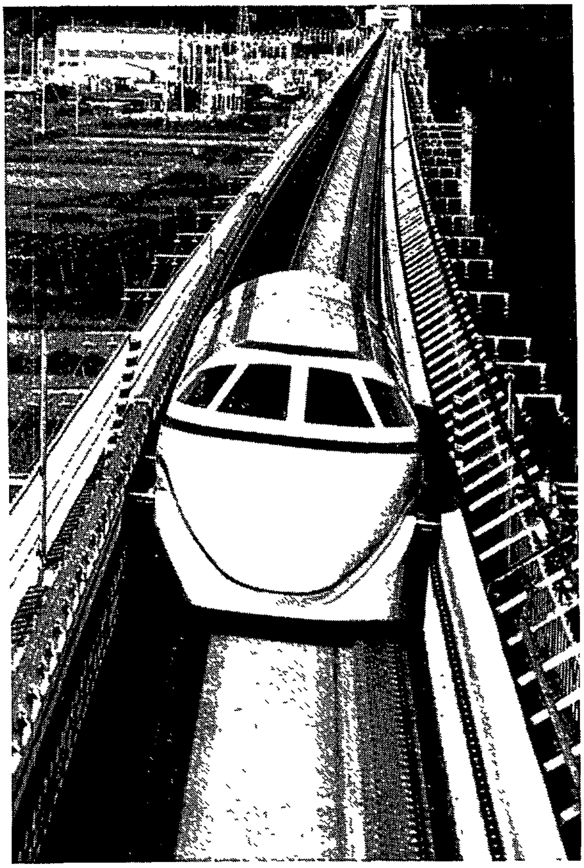

Fig. 2. — MLU vehicle on the track.

on two overlapping layers in the side wall track. This overlapping reduces the electromagnetic variations and also the a.c. losses in the superconducting coils which are that way better protected from quench. The power is supplied by two substations with GTO thyristor inverters leading to a possible increase of the frequency compared to the cycloconverters used for the previous test track. The enhancement of the frequency reduces the magnet pole pitch. The trains would be articulated with the bogies supporting the superconducting coils between the cars. This configuration reduces the magnetic field for the passengers, but a magnetic shielding should be perhaps provided. The dimensions of the cars should be 20 m long (28 m for end cars) 2.9 m wide and 3.3 m high, with a passenger capacity of 64. Each bogie carries two superconducting magnets in both its cold box and cryogenic fluid tanks (Fig. 4), two helium compressors, the retractable system for support and guidance, and emergency landing gear and damping systems. Aluminium alloys and carbon fibre composite materials are widely used for lightness.

1.4 AMERICAN PROGRAM [6]. — In 1990 the NMI (National MagLev Initiative) was created to evaluate the impact of levitation trains in the United States. Additional impetus was supplied in 1991 by the ISTEA (Intermodal Surface Transportation Efficiency Act) which established a « National Magnetic Levitation Prototype Development Programme », a six year $ 725 million programme. This programme, directed by a federal committee, would incorporate a track not

Table II. — *Characteristics of MLV 002 vehicle.*

Dimensions	22 x 3 x 3,7 m^3
Weight	17 tons
Levitation clearance	110 mm
Maximum speed	420 km/h
Seating capacity	44
SC magnet	2 x 6 poles
dimension, weight	1.7 x 0.5 m^2, 77 kg
type	race track
magnetomotive force	700 kAt
pole pitch	2.1 m
Material	NbTi, 1 : 1.06
max. field	5.1 T (550 kJ)
Propulsion	Synchronous motor
Max force	79.4 kN
Frequency	0-28 Hz
Voltage, current	5.8 kV, 900 A

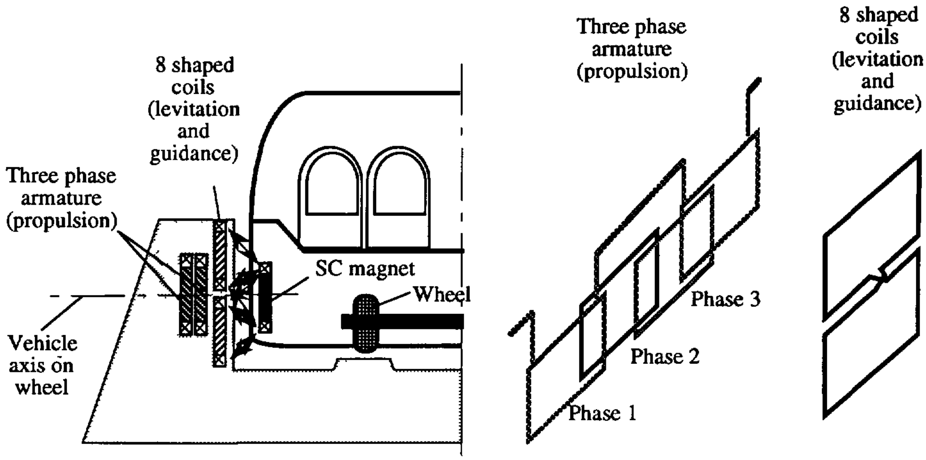

Fig. 3. — Schematic structure of the Japanese MagLev train.

less than 19 mile long with a guideway switch and an interface with an existing mode of transportation. Among the specifications required are speeds up to 135 m/s, high accelerations (0.16 g's), climb grades of 35 ‰ at full speed and 100 ‰ at reduced speed and short radii of curvature (400 m). A complete report from the NMI should be completed and considered before the launching of this programme. More recently the Clinton administration has planned funds for « High Speed rail and Maglev ».

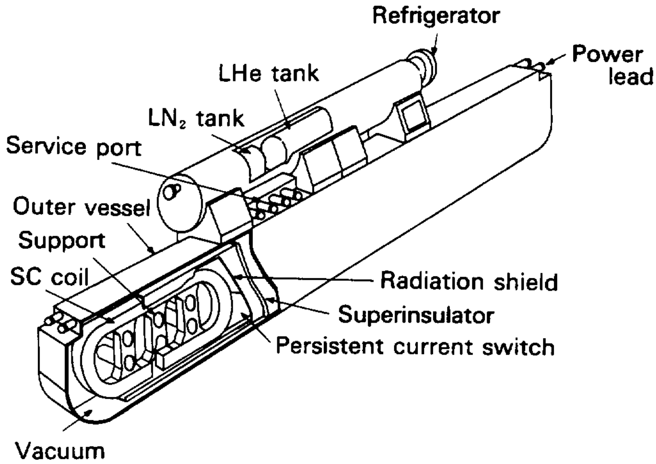

Fig. 4. — Cryogenic system (magnet, cryostat and refrigerator) of the Japanese train [5].

Contrary to Japaneses and Germans which are involved in programmes since many years and have already defined their basic solutions, Americans have no preferential design. This « clean slate » provides opportunities for innovative ideas and development of new MagLev concepts. They consider basic studies about subjects such as magnetic suspension, guidance and propulsion, power conditioning technologies, power transferring and control, costs, safety, environmental effects..

Four contracts were issued in 1991 for definition studies of new MagLev concepts. The four teams (Bechtel team, Grumman team, Magnetplane International team and Foster-Miller team) have rather different projects, but they all involve using superconducting windings and a linear synchronous motor for propulsion.

The Bechtel group proposes superconducting magnets distributed in the vehicle interacting with a « ladder track » for suspension and guidance.

The Grumman team is the only group involved in the electromagnetic levitation with a design close to the German TR07. Nevertheless the actively controlled iron-pole magnets on the vehicle are superconducting providing thus a 50 mm air gap (around 10 mm for TR07).

The magnet plane team works on an idea developed in the seventies by MIT [7]. The track consists in continuous sheet bended into a semi circular arc surrounded the vehicle bottom which contains superconducting distributed pancake windings. This geometry provides a high ride quality due to the possible self banking of the vehicle.

The foster Miller group is involved in the electrodynamic system using coils in the guideway for levitation and propulsion and discrete superconducting magnets on board. The supply of the linear synchronous motor is original in that it occurs only in the vicinity of the vehicle using high speed power electronics switches which improve the motor efficiency.

2. MHD sea-water propulsion.

2.1 INTRODUCTION. — The first MHD studies were carried out in the United States, during the sixties. As shown farther, the need for high magnetic inductions (> 5 T) in large volumes (several m^3) for the MHD propulsion to be interesting, from an efficiency point of view slowed its development. The present development level of superconducting winding makes it possible to consider practically this technology, and numerous programs throughout the world are in progress. The MHD propulsion offers potential advantages such as high efficiency and speeds, an enhanced maneuverability and survivability, a better payload flexibility but above all an increased stealth. The latter explains the military interest in the possibility of building an undetectable submarine as suggested in the Tom Clancy novel : « Red October ».

2.2 PRINCIPLE. — The MHD propulsion may be inductive (a.c. MHD) or conductive (d.c. MHD) (Tab. III).

Table III. — *Comparison between a.c. and d.c. MHD thrusters.*

		MHD d.c.	MHD a.c.
Inductor	system	d.c. winding	multiphase a.c. winding
	supply	no in persistent mode	multiphase, high reactive power
Armature	system	electrodes & sea water	sea water
	power supply	d.c.	no
Magnetic signature		low with adapted configuration	higher
Efficiency		better	lower
Cryogeny		very low losses in persistent mode	a.c. losses for superconductors need for current leads
Problems		electrodes, sea water electrolyse (partially solved)	superconducting a.c. winding, reactive power (to be solved)

The a.c. MHD operates as a linear asynchronous electrical motor. Multiphase windings, on board, create a travelling magnetic field wave in water. Currents are naturally induced in the conductive sea water and their interaction with the magnetic field propels the ship. The speed of the ship is linked to the speed of the field itself proportional to the frequency of the multiphase excitation currents. In its principle, a.c. MHD is attractive as it does not use electrodes in the sea water and solves the related problems. Nevertheless the advantages stop there. A.c. MHD needs multiphase superconducting windings supplied with variable frequency currents. These windings have still not yet reached a sufficient degree of advancement. The total absence of losses in a superconducting winding is only true if the current is direct and the field around it constant. The eighties have seen the emergence of superconducting strands with very low a.c. (50 Hz) losses [8], but difficulties still remain in particular, for high current capacity (several kA) cables. Frequencies, for MHD propulsion, would be low (a few Hz) and would reduce the stresses on superconducting windings, but the losses, though low, significantly penalise the cryogenics in particular the weight and bulkiness of the helium refrigerator. Moreover the reactive power would be very high (in the order of 10^9 Var for submarines) and would lead to additional difficulties and problems.

The d.c. MHD is based on the interaction between a magnetic induction, created by a d.c. electromagnet on board, and d.c. current, perpendicular to the field, imposed by a voltage difference between two electrodes in the conductive sea water. An opposing electromotive forces appears linked to the ship's displacement. The variation of the current or of the magnetic induction may adjust the propulsion force but basically only the current is controlled as the superconducting magnets are operating in persistent mode.

The electrodes in the sea water have to fulfil several electrical, mechanical and chemical requirements for long operating service and at a reasonable cost. Moreover, a partial electrolysis of the sea water occurs and produces bubbles which are undesirable for reasons of stealth. The ideal material for electrodes has not yet been found, but studies have been carried out for carbon, noble metals or compounds like $TiRuO_2$, $TiIrO_2$..

The power is supplied from Diesel engines, gas turbines or small nuclear reactor. The electrical power level is some tens MW in present submarines. The huge magnetic energy stored in the superconducting magnet (several GJ) could serve as an emergency power supply in case of failure of the main system [9].

As for the a.c. MHD, the d.c. MHD may be external (Fig. 5) or internal (flow channelled in a duct). Nevertheless as one of the interests on this system is its potential for stealth, the acoustical signature must not be substituted by a magnetic signature which is easy to detect. An essential characteristic for the excitation magnet would be its leakage field which has to be as low as possible. Currently the systems with internal MHD channels are, for this reason, the most studied systems, as the induction is better confined. The magnetic stealth must be naturally obtained as active (coils) or passive (magnetic materials) shielding increases the weight which is already a sensitive parameter. From this point of view the toroidal configuration is ideal and the systems under study now are close to this configuration with an annular MHD channel around the hull delimited by the active parts of the magnet and by the electrodes (Fig. 6).

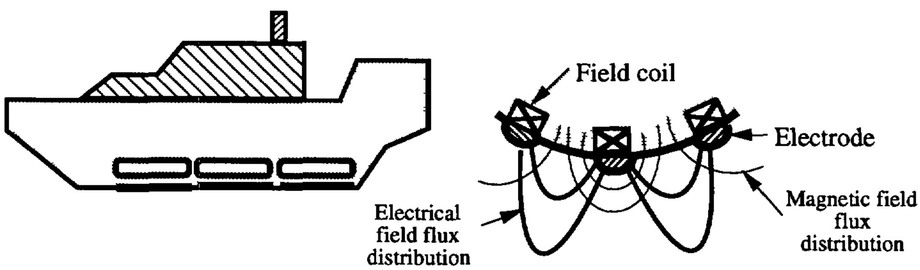

Fig. 5. — Ship propelled by d.c. MHD (external system).

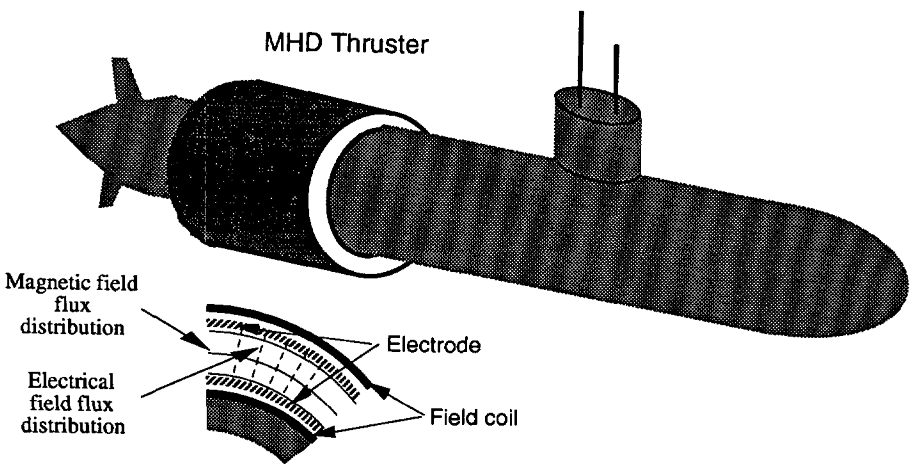

Fig. 6. — Annular MHD thruster for a submarine.

Considering a thrust proportional to the square of the speed, an approximate expression for the efficiency is given by :

$$\eta = \frac{B^2}{B^2 + \frac{\alpha \rho v}{\vartheta_{\text{MHD}}}}$$

B : magnetic induction, v : speed, ρ: sea water resistivity, ϑ_{MHD}. MHD volume, $\alpha : \frac{\text{magnetic force}}{\text{square of the speed}}$

This expression does not take into account the losses linked to the partial electrolysis of the sea water. It shows the requirement for a high induction level to a great extent due to the high resistivity of sea water (0.25 Ωm, 10^5 more than Cu) which leads to important ohmic losses in the water. The efficiency decreases with the speed of the ship. As an example of magnitude for a speed of 10 m/s, the overall efficiency could reach 60 % and 50 % for magnetic inductions respectively of 10 T and 7 T but only 18 % for 2 T. For comparison conventional efficiency is about 40 %. The present advances in superconducting d.c. magnets make it possible to consider useful induction levels of 6-7 T with NbTi at 4.5 K, up to 8-9 T with NbTi using helium II at 2 K like for the superconducting tokamak Tore Supra [10]. The use of Nb_3Sn would increase the field : 9-10 T at 4.5 K. Compounds with transition metals like Nb_3Sn, Nb_3Al, Nb_3Ge (A15 compounds) have a higher temperature margin compared to NbTi and may be interesting materials, taking into account the requirements for the magnet (vibrations, impacts) but their technical development is not so advanced except for Nb_3Sn and their use is more difficult than with NbTi. The induction level is not the only parameter to consider. This induction level and the volume to be magnetized lead to huge amounts of magnetic energy of the order of one tenth of a 10^9 J for submarines, and then to huge mechanical stresses. The mechanical structure has to be strong to resists to these forces very rigidly. As a matter of fact the displacement, even micrometric, of a superconducting strand in a magnetic field may lead to its quench which has to be absolutely avoided. For embarked materials, especially for military uses, these stresses are enhanced by the need to fulfil impacts. Moreover this structure must be light and must assume a neutral buoyancy. The realization of lighweight high field magnets would be one of the challenges for MHD technology. The present techniques using steels are too heavy : in the international project on nuclear fusion ITER the toroidal coils would have a structure weight of 10 000 tons including 770 tons of superconducting materials but without the cryostat vessels (6 T on the toroidal axis, 13 T peak on the superconductor and a magnetic energy of 106 GJ). The theoretical limits are nevertheless high. The virial theorem links the magnetic energy to the mass of coil structure by the expression [11] :

$$W_{\text{mag}} = \frac{\sigma_{\text{u}}}{\rho} (M_{\text{t}} - M_{\text{c}})$$

W_{mag}. magnetic energy, σ_{u}. allowable stress, ρ: density, M_{t}: mass in tension, M_{c} : mass in compression.

Assuming a structure is only in tension, the theoretical limit of the magnetic energy by mass unity is given by the specific energy σ_{u}/ρ of the structural materials. Graphite epoxy composites offer much higher values than classical steels : 150 kJ/kg compared to 30 kJ/kg. For comparison, present superconducting magnets have a specific energy of the order of 10 kJ/kg. A value of 50 kJ/kg may be achievable in a near future [11].

As for MagLev vehicles, the magnetic induction, constant in the ship referential, may be created by superconducting magnets operating in persistent mode ; that is to say, short circuited coils. After the magnet has been energized by a current from a power source and after the magnet terminals have been shorted out with a superconducting link, the power supply may be suppressed and the current leads may be removed. The persistent mode is very interesting as the current lead losses are a major part of the total cryogenic losses. In these conditions, the power of the helium refrigerator on board may be very low if the cool down is carried out on land.

2.3 PROGRAM IN JAPAN [12]. — In 1985 the Ship and Ocean Foundation undertook research about civilian ships propelled by MHD. This project gathered together officials and people from universities and industry. It included the manufacturing of a complete experimental ship called Yamato I. This ship of significant scale was completed in 1991 and is under tests at sea now. This, the first big ship with MHD propulsion, is a surface ship whose main characteristics are gathered in table IV. Yamato I is propelled by two electromagnetic thrusters located in two bulges in the hull under the ship (Fig. 7). Each thruster is composed of six superconducting dipoles with a bore of 360 mm (MHD channel $\phi = 240$ mm) in a single cryostat fed by an on-board helium refrigerator. The dipoles are arranged to minimize the leakage of the magnetic field outside the thruster. The tests have been performed with an induction of 2 T, with a maximum value of 3 T. The latter led to a quench after 20 min of operation. The experimental data agree with the theoretical calculations.

The performances of Yamato I are very low, but we have to note that it is the first experimental ship with MHD thrusters. The objectives were to prove its feasibility and the Japanese capacity to develop a complete, difficult, high technology project. More so than in the case of the MagLev vehicles, Yamato I is an operation carried out for reasons of prestige.

Table IV. — *Some characteristics of ships propelled by MHD thrusters (the submarine is a theoretical study).*

Ship type		Demonstration Yamato I	Nuclear submarine
	weight	280 tons	10 000 tons
	dimensions (m)	L = 30 - l = 10 - h = 3.5	L = 110 m - ø = 12 m
Thruster	number and type	2 x 6 cylindrical	1 annular
	active length	3 m	15 m
	total length	5.4 m	17 m
	channel bore	ø = 240 mm (2 x 6)	1.5 m
	weight	2 x 29 tons (2 x 18 tons)	1060 tons
Magnet	coil	saddle shape (dipole)	en U (torus)
	useful field	4 T	6 T
	max. field	6.5 T	9 T
	storaged energy	2 x 18.6 MG	13.5 GJ
	supra.	NbTi	NbTi 180 A/mm^2
	conductor	Rutherford	Cable in conduct 80 kA
	cooling	He I, 4.2 K	He I, 4.2 K
Refrigerator		2 x 11 W à 4.4 K	180 kW warm - 11 tons (with current leads)
Speed		4 m/s (8 knots)	15 m/s (30 knots)
Efficiency		< 2 %	

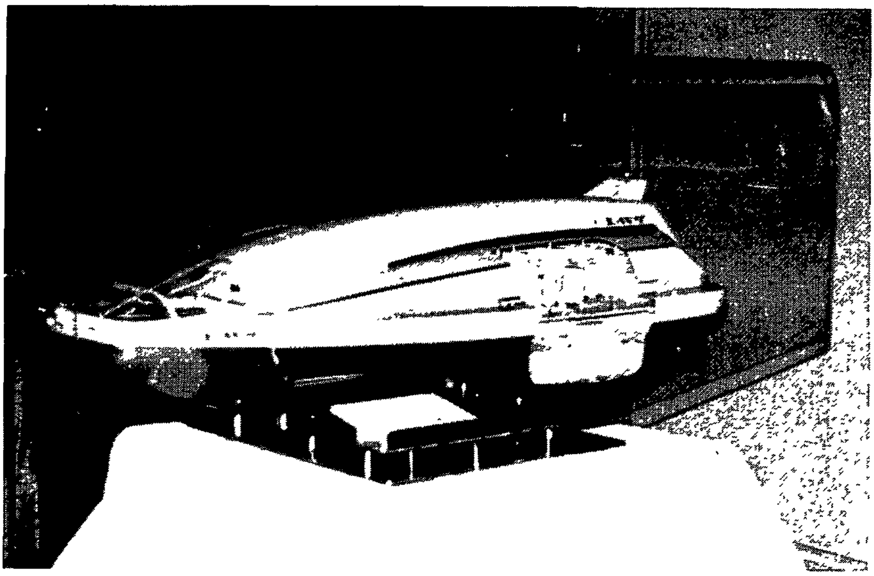

Fig. 7. — Yamato I, MHD ship (Height : 3.5 m, Width : 10 m, Length : 30 m).

2.4 PROGRAMS IN THE UNITED STATES. — The first studies of MHD were carried out in the United States in the sixties, but were later interrupted. Since then naval research into propulsion has concerned the classical propulsion, but using superconducting motors (in particular the experimental ship Jupiter II with a homopolar superconducting motor of 2.2 MW). Programs about MHD were re-continued at the end of the eighties. They are financed by DARPA (Defence Advanced Research Project Agency) and the Naval Research Technology Office. These programs should provide a better theoretical knowledge of MHD phenomena and some tests on the key points. The experimental tests use the flow loops at the NUWC in New Port, or at Argonne National Laboratory with a large Superconducting magnet. The description of a MHD submarine project [9] (Tab. IV) enables the definition of some of the major points.

2.5 PROGRAM IN C.E.I. [13]. — The Russian are certainly involved in important programmes themselves. They are studying in particular a solution of d.c. MHD with a special geometry using a solenoid magnet with a screw MHD channel inside. The advantages of this configuration are simplicity and the light weight of the magnet system, but the hydraulic and Joule losses are heightened compared to classical duct channels. The real system is composed by two concentric solenoids for active magnetic shielding with two screw channels.

2.6 PROGRAM IN FRANCE [14]. — France is interested in MHD studies. A centre for applications of MHD called PAMIR has been created throught co-operation between a laboratory (LEGI/IMG) the C.E.A (Commissariat à l'énergie Atomique, CEN Cadarache) and two industrials (Framatome and DT21). The objective of PAMIR is the development of industrial applications of MHD, but not, for instance, of propulsion. A program has been issued by the DRET (Direction des Recherches Etudes et Techniques de la Délégation Générale pour l'Armement), involving Jeumont Industrie and four laboratories in Grenoble (LEGI-IMG, Madylam, CREMGP and LEG). This program will attempt to carry out general studies on the systems : fluid mechanics aspects (flow in MHD duct, evaluation of drag force, . .), numerical modelling with coupling between fluid mechanics and electromagnetism, taking into account the non uniform distribution of magnetic fields, electrochemical aspects (seawater properties, electrodes, phenomena modelling, ..), superconducting magnets (configuration and shape, magnetic signature and its reduction, magnetic shielding), overall performance prediction. An experimental programme is carried out especially for electrochemistry studies using a seawater laboratory close loop (electrolysis, corrosion of electrodes, gas production, .).

3. Refrigeration on board.

There are two solutions to keep the superconducting magnets at low temperature. Either a sufficiently large amount of liquid helium may be stored on the vehicle between two fillings, or a helium refrigerator on board may provide the cryogenic losses. The first solution, of minimum weight for the vehicle, provides a high efficiency, large capacity liquefaction in large plants, but requires skilled persons to carry out the transferts and brings constraints and operational complexity. It cannot be applied to MHD ships. If the cool down is made by a land-borne large capacity system, the helium refrigerator required for the superconducting MHD magnet does not pose any problems : for submarines (for example from Tab. IV) the power amounts to some hundreds of watt (depending on the presence, or lack of it, of current leads). It corresponds to a system whose weight and volume are, respectively, roughly 5 to 10 tons and 10-15 m^3 ; low figures compared to those for the submarine (10 000 tons and 12 000 m^3). On board refrigerators for MagLev vehicles are much more flexible, but this requires the developement of small unit helium refrigerators with low weight and bulkiness, very high reliability and which are less sensitive to vibrations. Such systems have been developed for satellites but for very small power (lower than 1 W to cool, for example, detectors) and are not always suitable for a levitated vehicle (power too low). Japanese researchers developed such a helium refrigerator [15] in 1979 and have since obtained some interesting performances.

Conclusion and perspectives.

MagLev vehicles and MHD are two possible applications of superconductivity. MagLev systems may be designed with conventional magnets but several people think that you cannot get good MagLev without superconductivity. Japanese MagLev trains have already reached an advanced degree of demonstration. Superconducting MagLev system is feasible from technical point of view but its challenge is to prove its economical interest compared to high speed trains except if speeds higher than 400 km/h are absolutely required.

For MHD there is no alternative to superconductivity as large volumes must be magnetized at high fields to get suitable performances. The studies have often stayed at the stage of theoretical designs whereas the first MHD ship of significant size, Yamato, shows very low performances. Nevertheless MHD propulsion offers an innovative solution with significant benefits. The increased stealth is perhaps one of the most interesting improvements if the magnetic signature may be reduced to a very low level. A lot of research and development are still needed to study and to solve the numerous difficulties related to MHD thrusters. One technical bolt is the superconducting magnet with a light mechanical structure able to withstand electromagnetic forces and impacts.

Superconductors with a high critical temperature would not greatly modify the structure of the magnets or of the cryostat except, of course, for a few simplifications. They will bring nevertheless a large gain for the refrigerator : at a given power, the weight and the volume of the nitrogen refrigerator are divided roughly by fifty compared to a helium refrigerator. Another advantage of the high T_c materials for moving systems is their much higher stability margin, as well as lower sensitivity for impacts, vibrations and a.c. losses. These superconducting oxides offer the opportunities of higher fields but limitations due to the electromagnetic stresses will occur.

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