SUPERCONDUCTIVITY: AN OVERVIEW AND AN ACCOUNT OF ITS APPLICATION TO MASS TRANSPORTATION SYSTEMS

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INDIA
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Dedicated to

My Parents

Certificate

The research work presented in this dissertation has been carried out in the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi – 110067. The work is original and has not been submitted in part or full for any other diploma or degree of any other University.

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(Akhilananda Kumar)

CONTENTS

1. SUPERCONDUCTIVITY

1.1 Introduction

Superconductivity is a property of a material that is characterized by zero electrical resistance and, ideally, zero permeability. Discovered in 1911 by Heike Kamerlingh Onnes[1], superconductivity is currently a vigorous field of research all over the world. As a matter of fact, since the mid-eighties of the last century to date, few areas of physics have attracted the attention given to it. Although part of the incentive to find better and more promising superconducting materials has to be credited to curiosity and academic interest, the principal incentive has been and continues to be the vast commercial potentials for applying superconductors. While our objective in this thesis is to review in some depth one or more applications of superconductivity, we would like to set the stage for it, in the next section, by beginning with a chronology of important experimental discoveries and the development of theoretical ideas in the field. Since these activities span nearly a hundred years, the chronology will be supplemented by only a brief commentary, where appropriate. The final section in this chapter delineates the scope of the thesis.

1.2 Chronology of experimental discoveries and development of theoretical ideas in superconductivity with brief comments

1890-1910 This is how it began. A topical problem was: how does resistivity (ρ) behave as one lowers the temperature of the sample? Dewar believed that ρ would $\rightarrow 0$ as $T \rightarrow 0$, whereas Kelvin believed that ρ would first decrease, and then increase indefinitely as $T \rightarrow 0$. To settle the issue, laboratories in Europe were trying to develop the cryogenic technology during this period.

1908 Kamerling Onnes succeeded in liquefying He and obtained a temperature as low as 4 K. The following table brings out the significance of this achievement.

Substance	H_2O	O_2	N_2	Ne	H_2	He
B.P. (K)	373	90	77	27	20	4
M.P. (K)	273	55	63	24	14	
Year		1883	1883		1898	1908

Temperature could be further reduced to 1.7 K at reduced pressure. With low temperature apparatus available, Onnes naturally turned to ρ v/s T behaviour. Initial metals used were platinum and gold. It was found:

(a) ρ falls, but does not become zero or infinity.

(b) The minimum ρ decreases as the impurity level of the metal decreases.

Therefore, Onnes turned to Hg which was the purest metal then available.

1911 Superconductivity was discovered by Onnes[1]. For Hg, ρ falls as T is lowered. ρ becomes zero not at absolute zero, but earlier (4.22 K) and remains zero thereafter (Fig.1.1). The new state of the matter was called the superconducting state. The temperature at which the transition from normal state to superconducting state occurs is known as the critical temperature T_c. In December 1912, he discovered that other metals, which could be made into wires at room temperature,could be made superconducting[2], namely tin (3.8 K) and lead (7.2 K). It was immediately realized that with wires of zero resistance, intense magnetic fields could be produced without iron cores.

Two dampeners in the practical applications of superconductivity: It was soon found that superconductivity is destroyed by:

(a) quite small current densities

(b) presence of quite ordinary magnetic fields.

There were two barriers to superconductivity:

(a) temperature barrier

(b) magnetic / current barrier.

1928-1930 At the Physikalisch-Technische Reichsanstalt near Berlin under the direction of Walther Meissner, three new important superconductors[3] were discovered:

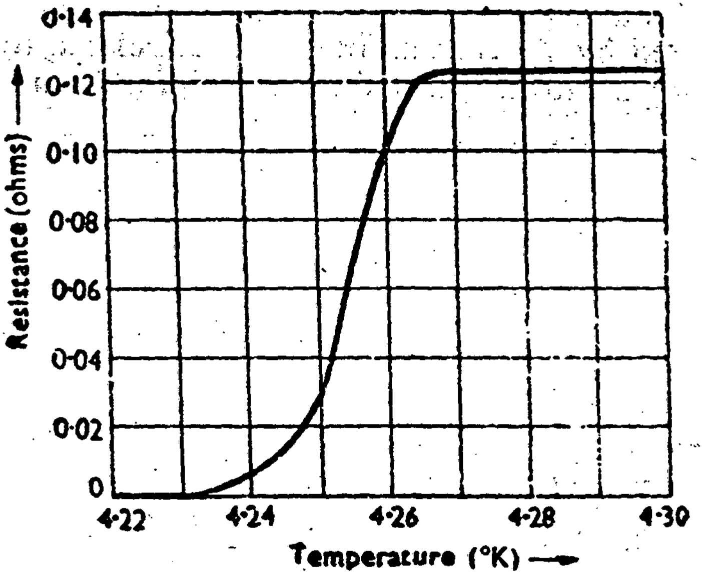


Fig.1.1: Resistance of mercury as a function of temperature; critical temperature $T_c = 4.2$ K.

(a) tantalum (T_c=4.4 K)

(b) thorium (T_c=1.4 K)

(c) niobium (T_c=9.2 K)

An alloy of niobium, Nb-47 wt% Ti, is now by far the most important commercial superconductor, with widespread use in magnets for magnetic resonance imaging (MRI) systems in hospitals as well as many other applications. Nb-based technology is also the current standard for digital superconducting circuits.

Meissner's group found that most of the transition elements in groups IV and V were superconducting. In Fig.1.2, a listing of the elemental superconductors with their locations in the periodic table is shown. The Meissner group also found a large number of carbides and nitrides with higher T_c, in particular NbC (T_c>10K).

1933 In 1933 an important discovery was made by Meissner and his student Robert Ochsenfield. Placing superconductors between the poles, of a magnet it was found that superconductors expel magnetic flux[4] from the interior (Fig.1.3). It means that superconductors are impervious to a magnetic field, i.e., superconductors are perfect diamagnetic substances (susceptibility<0).

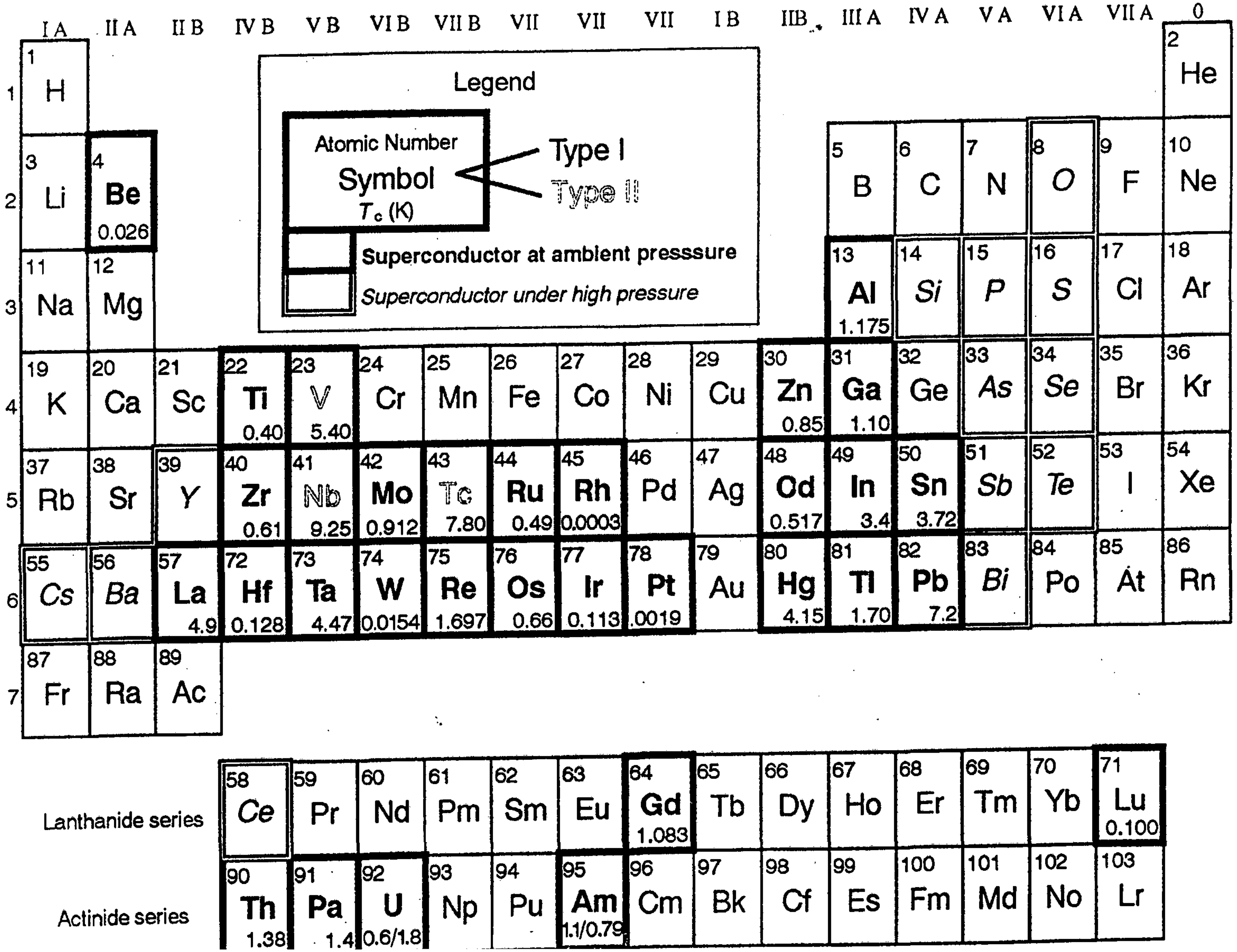
Following Meissner effect, the question was raised: is a superconductor merely a perfect conductor (a material with ρ=0 for some T<Tc), or is there something more to superconductivity than perfect conductivity?

It was found – via Gedaken experiments and experimentation – that while a superconductor has, of course ρ=0, it differs from a perfect conductor in its behaviour in a magnetic field. To bring out this difference, let us note a fundamental property of a perfect conductor: internal magnetic flux linked with it cannot change. This is easy to see:

(a) Place a perfect conducting ring (Fig.1.4) in a magnetic field of uniform flux density B_a. Flux associated with the ring is

$$\Phi = B_a A$$

(b) Change B_a; while it is changing, currents are induced to oppose the change (Lenz's law).



Legend

Atomic Number
Symbol
T_c (K)

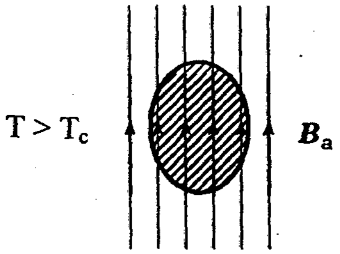
Type I
Type II

Superconductor at ambient presssure

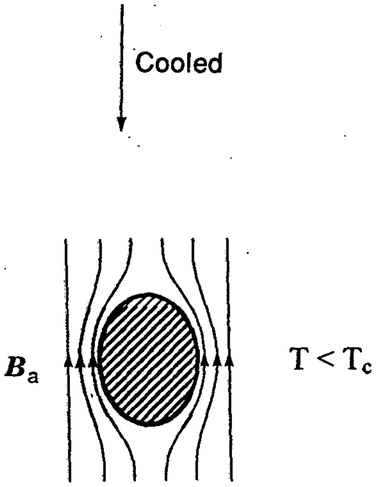
Superconductor under high pressure

	IA	IIA	IIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 **Be** 0.026											5 B	6 C	7 N	8 *O*	9 F	10 Ne
3	11 Na	12 Mg											13 **Al** 1.175	14 *Si*	15 *P*	16 *S*	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 **Ti** 0.40	23 V 5.40	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 **Zn** 0.85	31 **Ga** 1.10	32 Ge	33 *As*	34 *Se*	35 Br	36 Kr
5	37 Rb	38 Sr	39 *Y*	40 **Zr** 0.61	41 Nb 9.25	42 **Mo** 0.912	43 Tc 7.80	44 **Ru** 0.49	45 **Rh** 0.0003	46 Pd	47 Ag	48 **Cd** 0.517	49 **In** 3.4	50 **Sn** 3.72	51 *Sb*	52 *Te*	53 I	54 Xe
6	55 *Cs*	56 *Ba*	57 **La** 4.9	72 **Hf** 0.128	73 **Ta** 4.47	74 **W** 0.0154	75 **Re** 1.697	76 **Os** 0.66	77 **Ir** 0.113	78 **Pt** .0019	79 Au	80 **Hg** 4.15	81 **Tl** 1.70	82 **Pb** 7.2	83 *Bi*	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac															
Lanthanide series				58 *Ce*	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 **Gd** 1.083	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu 0.100	
Actinide series				90 **Th** 1.38	91 **Pa** 1.4	92 **U** 0.6/1.8	93 Np	94 Pu	95 **Am** 1.1/0.79	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Fig.1.2: Elemental superconductors.



Normal state



Superconducting state

Fig.1.3: Meissner effect in a superconductor cooled in a magnetic field; lines of magnetic induction are ejected at the transition of normal state into superconducting state.

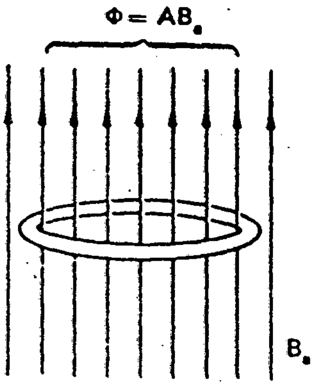


Fig.1.4: A perfect conducting ring placed in a magnetic field $\Phi = B_aA$.

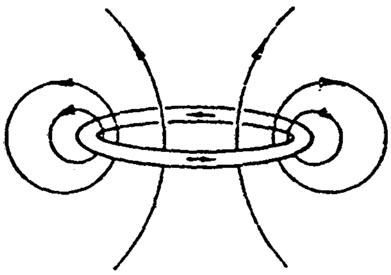


Fig.1.5: Flux is maintained through induced circulating current.

(c) $-A\frac{dB_a}{dt} = Ri + L\frac{di}{dt} = L\frac{di}{dt}$ (since, $R = 0$)

(d) $\frac{d}{dt}[AB_a + Li] = 0$

$\therefore (AB_a + Li) = \text{flux} = \text{constant}.$

In particular, this flux will be maintained (Fig.1.5) even when the applied magnetic field is switched off (through induced circulating current).

Inside of a perfect conductor, there may or may not be a flux density when external field is switched off (Fig.1.6), while a superconductor never allows a magnetic flux density to exist in its interior (Meissner effect). The behaviour of a perfect conductor in a magnetic field depends on its 'history' while the behaviour of a superconductor in a magnetic field does not depend on the sequence of events or its 'history' (Fig.1.7). Therefore, the laws of reversible thermodynamics may be applied to superconductors (if need be).

Important remark: We had said earlier that a superconductor has two fundamental attributes, namely zero resistivity and perfect diamagnetism. Let us now note that $\rho=0$ for superconductors is true only for direct currents. For ac currents, at $T=0$, this is true only upto a limiting frequency. At $T\neq0$ but $T<T_c$, ρ has a small value at all frequencies.

Behaviour of a superconductor when both temperature and applied magnetic field are varied: Superconductivity is destroyed when $T>T_c$ and also when $H>H_c$ (Fig.1.8).

Experimentally,

$$H_c(T) = H_c(0)\left[1 - \left(\frac{T}{T_c(H=0)}\right)^2\right]$$

The Fig.1.8 may be viewed as a phase diagram—the lower left region of the figure representing the superconducting state, and the upper right region the normal conducting region.

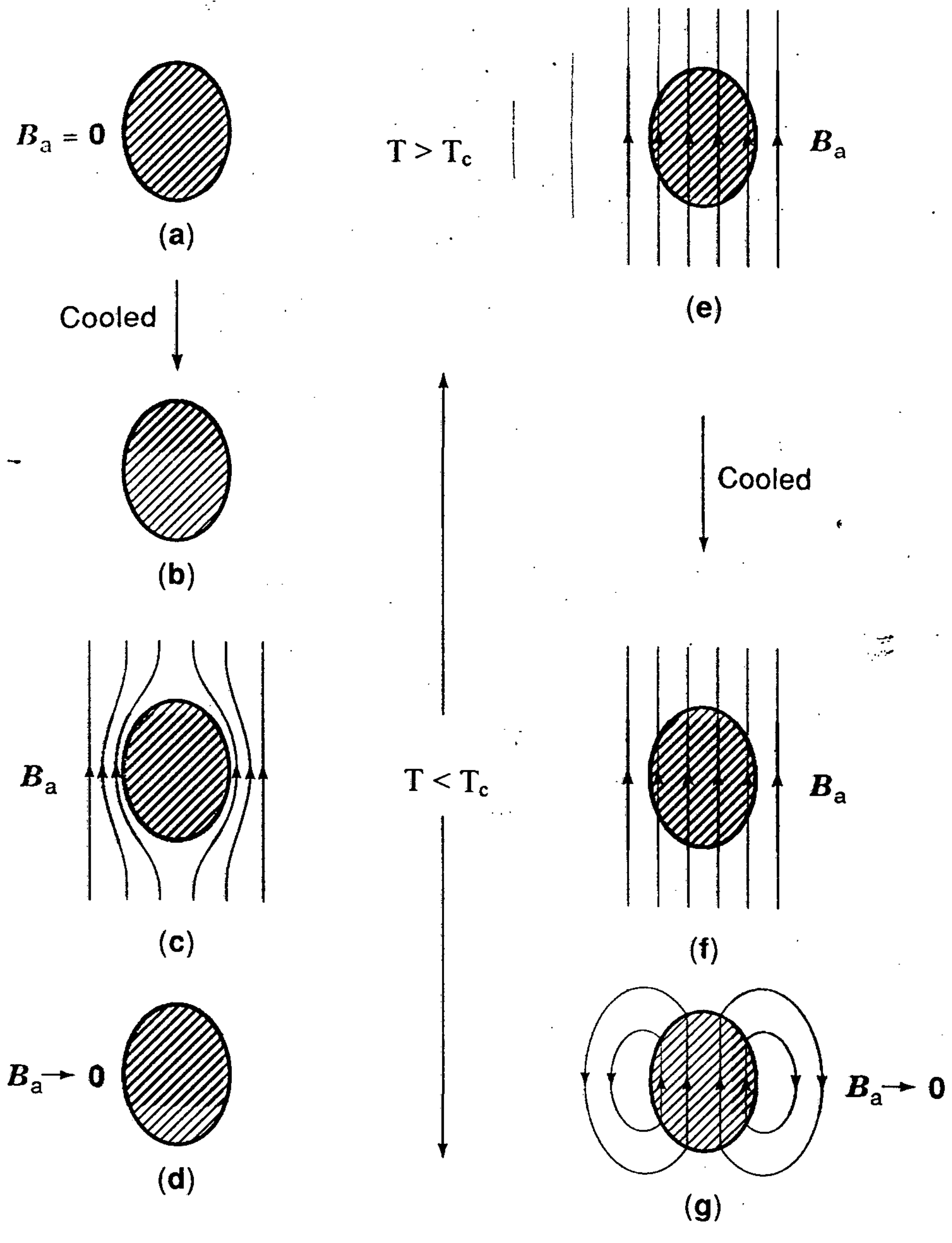


Fig.1.6: Magnetic behaviour of a perfect conductor. (a)-(b) Specimen becomes resistanceless in absence of field. (c) Magnetic field applied to resistanceless specimen. (d) Magnetic field removed.

(e)-(f) Specimen becomes resistanceless in applied magnetic field. (g) Applied magnetic field removed.

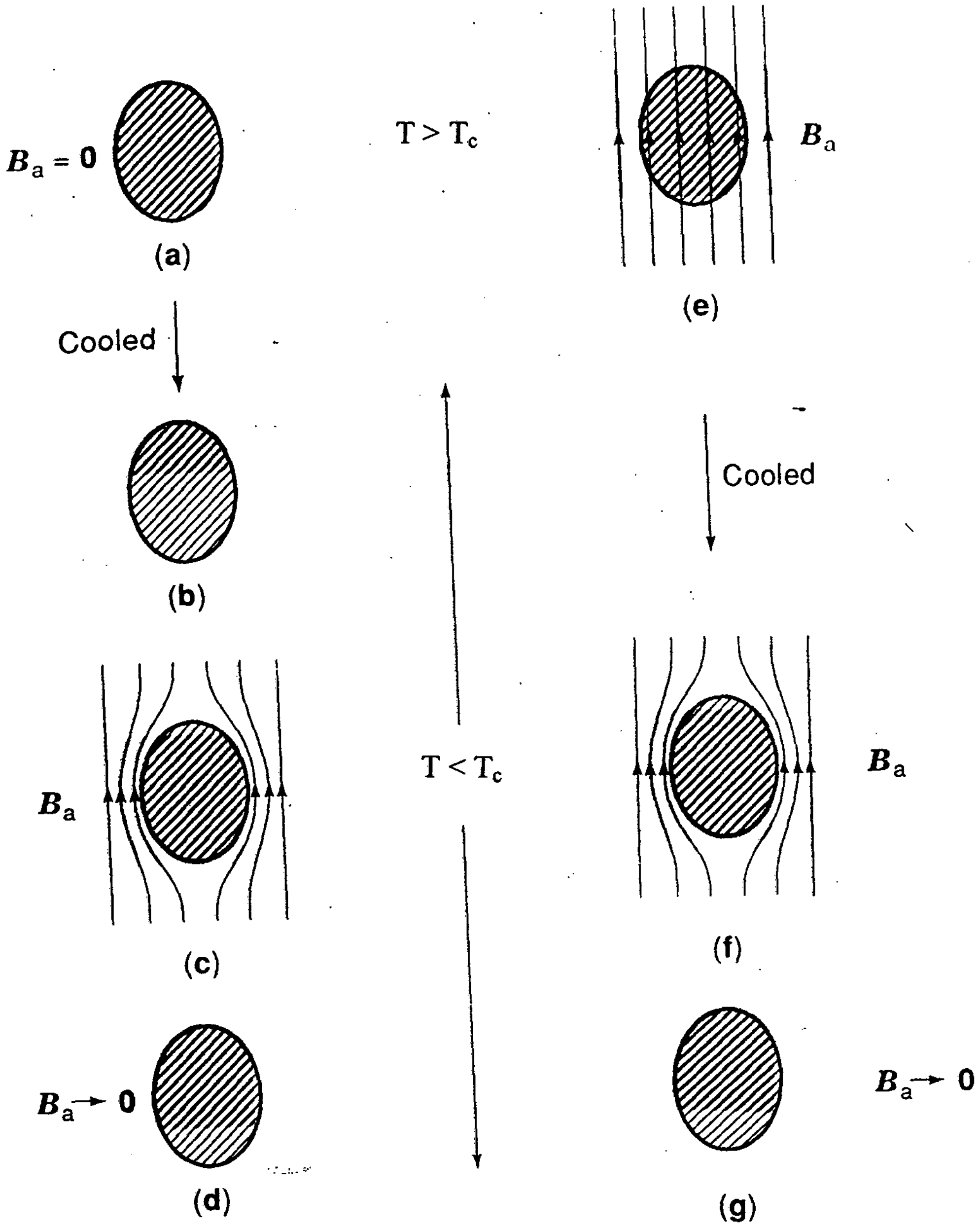


Fig.1.7: Magnetic behaviour of a superconductor. (a)-(b) Specimen becomes resistanceless in absence of magnetic field. (c) Magnetic field applied to superconducting specimen. (d) Magnetic field removed.

(e)-(f) Specimen becomes superconducting in applied magnetic field. (g) Applied magnetic field removed.

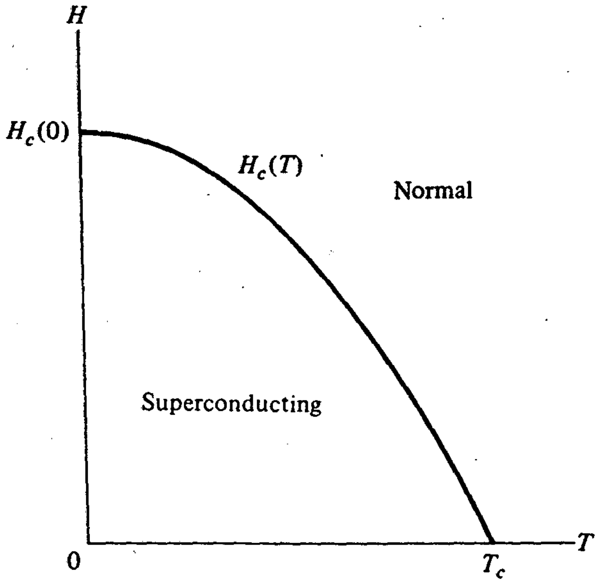


Fig.1.8: Temperature dependence of critical field.

1934 Gorter-Casimir two-fluid model:

Thermodynamics of a superconductor in a magnetic field.

$\rho=\rho_s+\rho_n$

where, ρ = density

ρ_s= density of superconducting state

ρ_n= density of normal state

or, $1 = \rho_s/\rho + \rho_n/\rho$

$\rho_s/\rho = 0,\ \rho_n/\rho = 1 \quad (H=0, T\geq T_c) \quad (T=0, H\geq H_c)$

$\rho_s/\rho = 1,\ \rho_n/\rho = 0 \quad (T=0) \quad (H=0)$

For, $0 < T < T_c$, two phases coexist.

Now, $B = H + 4\pi M$

Where, H : applied magnetic field

M : magnetic moment

B : magnetic induction

Volume = unity

$$\therefore M = -\frac{H}{4\pi}$$

For a superconductor, B = 0

Now, $G = H' - TS - MH$

$= E + pV - TS - MH$

or, $dG = dE + pdV + Vdp - TdS - SdT - HdM - MdH$

$= Vdp - SdT - MdH \quad$ (as, $dE = TdS - pdV + HdM$)

or, $dG = -MdH$ (for, p and T constant)

For normal state, M = 0

$$\therefore dG_N = 0$$
$$\therefore G_N(H) = G_N(0)$$
$$\therefore G_N(H_c) = G_N(0)$$

For superconducting state,

$$\begin{aligned} dG_s &= -MdH \\ &= \frac{H}{4\pi}dH \end{aligned}$$

$$\therefore \int_0^H dG_s = \int_0^H \frac{H}{4\pi}dH$$

$$\therefore G_s(H) - G_s(0) = \frac{H^2}{8\pi}$$

For $H = H_c$, $G_s(H_c) = G_s(0) + \frac{H^2}{8\pi}$

In equilibrium at $H=H_c$, we have

$$G_N(H_c) = G_s(H_c)$$

$$\therefore G_N(H_c) = G_s(0) + \frac{H^2}{8\pi}$$

Therefore, $G_N(0) = G_s(0) + \frac{H^2}{8\pi}$

For a normal metal, susceptibility is very small when H=0, Gibb's free energy for superconducting state is lower than G in the normal state. Since a system tends to be in the lowest energy state available to it, it is in the superconducting state.

Why does a superconductor expel magnetic flux only upto $H=H_c$? (- dG) gives the measure of useful work that a system can perform (other than work of expansion). Expulsion of flux requires work to be done when (-dG) is used up, the specimen can no longer prevent entry of flux; the specimen becomes a normal metal.

1935 London Brothers (F.& H.) applied laws of electrodynamics to the two-fluid model[5]. Rather than writing $\rho=\rho_s+\rho_n$ (densities), write for total current density (J) the expression (in cgs units):

$$\vec{J} = \vec{J}_s + \vec{J}_n$$

$\vec{J}_n$ satisfies: $\vec{J}_n = \sigma \vec{E}$ (ohm's law)

where, σ = electrical conductivity

What about $\vec{J}_s$?

London's Postulate: $\vec{J}_s \propto \vec{A}$

where, $\vec{A}$ is vector potential.

(Recall, $\vec{B} = \vec{\nabla} \times \vec{A}$, $\vec{E} = -\vec{\nabla}\Phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t}$)

$$or, \quad \vec{J}_s = \left(-\frac{c}{4\pi\lambda_l^2}\right)\vec{A}$$

where, c = velocity of light

λ_1 = length

$$\vec{\nabla} \times \vec{J}_s = \left(-\frac{c}{4\pi\lambda_l^2}\right)\vec{\nabla} \times \vec{A}$$

$$or, \vec{\nabla} \times \vec{J}_s = \left(-\frac{c}{4\pi\lambda_l^2}\right)\vec{B} \quad \text{(Londons' equation 1)}$$

This equation leads to Meissner Effect:

Maxwell's equation (under static conditions) is given by

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c}\vec{J}$$

$$\Rightarrow \vec{\nabla} \times (\vec{\nabla} \times \vec{B}) = \frac{4\pi}{c}(\vec{\nabla} \times \vec{J})$$

$$\Rightarrow -\vec{\nabla}^2 \vec{B} = \frac{4\pi}{c}\left(-\frac{c}{4\pi\lambda_l^2}\right)\vec{B}$$

$$\Rightarrow \vec{\nabla}^2 \vec{B} = \frac{1}{\lambda_l^2}\vec{B} \qquad \text{..............................(1)}$$

$\vec{B} = \vec{B}(r)$ = a constant, cannot be a solution of (1), since then LHS = 0 and RHS $\neq 0$.

$\therefore$ a uniform magnetic field $\neq 0$ cannot exist in a superconductor

(uniform $\Rightarrow$ same value at all $\vec{r}$).

The only uniform solution is $\vec{B} = 0$.

However, a non - uniform magnetic field (function of $\vec{r}$) can exist in a magnetic field for suitable geometrical solution of (1):

$$B(x) = B(0)\exp\left(-\frac{x}{\lambda_1}\right)$$

At a distance x = λ_l, the field inside falls to 1/e of its value at the plane boundary (Fig.1.9). This distance is called London penetration depth ≈ 500 Å (pure superconductor).

First London equation gives:

$$\vec{B} \propto \vec{\nabla} \times \vec{J}_s.$$

What about $\vec{E}$ in a superconductor ?

$$\vec{E} \propto \lambda_l^2 \frac{\partial \vec{J}_s}{\partial t} \qquad \text{(replaces } \vec{E} = \frac{1}{\sigma}\vec{J}_n\text{)}$$

1935(Later Part) We recall, London's postulate:

$$\vec{J}_s \propto \vec{A}$$

$$\Rightarrow \vec{\nabla} \times \vec{J}_s = \text{constant}$$

$\Rightarrow$ Expulsion of $\vec{B}$ (Meissner Effect).

F. London suggested that the above property (diamagnetism) might follow from quantum mechanics if there was a 'rigidity' or stiffness of wavefunction ψ of the superconducting state such that ψ was essentially unchanged by the presence of an external magnetic field. Rigidity means, naively, that all the superconducting electrons are somehow 'locked together'.

Put a superconductor in a magnetic field, flux is not allowed inside because of rigidity. Increse magnetic field – a stage will come when superconductivity will give way – it will become normal. This means that there ought to be a gap in the excitation spectrum of a superconductor which separates the energy of superconducting electrons from the energy of electrons in the normal state.

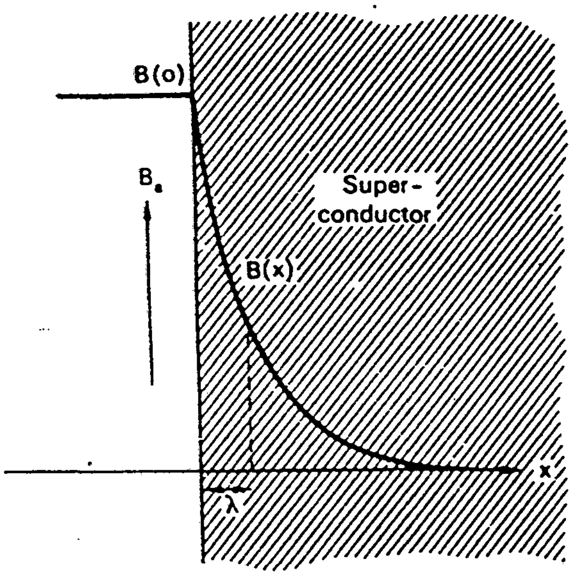


Fig.1.9: Variation of flux density at boundary of a superconductor.

How electrons are locked together? Shouldn't they repel each other? Concept of such a gap played an important role in the solution given by BCS.

1950 Ginzburg-Landau Theory[6] generalizes London's Theory in two important ways:

(a) it allows n_s to become $n_s(\vec{r})$

(b) it introduces an order parameter $\left|\Psi(\vec{\mathrm{r}})\right|^2 = \frac{n_s(\vec{r})}{n}$ which describes a macroscopic quantum state.

Now, in somewhat ad hoc manner they write down:

The total magnetic contribution to the free energy of the superconducting state

$$= \frac{\hbar^2}{2m} \int \Psi^* \left[i\vec{\nabla} + \frac{eA}{\hbar} \right]^2 \Psi dV$$

and proceed to determine Ψ and A which make the total free energy a minimum subject to boundary conditions.

Where,

$\vec{A}$ is the magnetic vector potential defined by $\vec{B} = curl\,\vec{A}$,

Ψ is the effective wave function such that $|\Psi|^2$ is equal to the density of superconducting electrons,

e = electronic charge,

m = electronic mass,

$\hbar = \mathrm{h}/2\pi$,

h = planck's constant,

Ψ^* = complex conjugate of Ψ,

V = whole volume of the specimen.

Significance of Ginzburg-Landau theory.

(a) It reduces to London's theory in the appropriate limit.

(b) It clarifies the relationships between penetration depth and coherence length.

(c) BCS theory reduces to it in the appropriate limit.

(d) It is much simpler to use (for engineers) than BCS.

1950 Even after a long period (1911-1950), there was yet no satisfactory theory. The work of Gorter-Casimir, London brothers and Ginzburg-Landau was phenomenological. In particular, there was no way of predicting just what substances might be superconductor, or at what temperature they would reach this state. At this stage Matthias and Hulm set out to find superconducting materials strictly by experiments. Their hope was that after they had tested a large numbe of substances, they would begin to see a pattern. They didn't know where to begin. They started from one end of the periodic table though it was labourous work indeed. Their findings (very important for practical purposes) were:

(a) Superconducting substances (elements or compounds) have an average of 2 to 8 valence electrons in outer unfilled shell.

(b) Of the above, those that have an odd number of electrons (3,5,7) become superconducting most easily (have higher T_c).

(c) Superconductivity is favoured by certain kinds of crystal structure and by the amount of empty space in the crystal (space not occupied by atoms).

Examples of usefulness of the rules:

(a)

	Molybdenum	Technetium	Ruthenium
Valence electrons	6	7	8
T_c	$< 1/10$ K	11 K	≈ 0.5 K

An alloy of molybdenum and ruthenium (equal part) has an average number of 7 electrons, it's $T_c = 10.6$ K.

(b) Silicon is not a metal or conductor of electricity. Cobalt has two qualities which totally disqualify it for a superconductor – it has 9 valence electrons and is strongly magnetic. Yet when silicon and cobalt are combined in a cubic structure, they become a superconductor since silicon neutralizes cobalt's magnetism and reduces the average number of electrons to the appropriate range.

(c) Ni and arsenic (compound) should be a superconductor but has not favourable crystal structure and number of valence electrons. If half of the Ni is replaced with the bulker pallidium, we get a superconductor.

1950 Flux quantization and persistent currents. Expulsion of magnetic flux from a superconductor refers to a body without holes. Consider now a body with a hole in a magnetic field of uniform flux density at T > T_c (Fig.1.10). Now cool it to a temperature T < T_c so that it is a superconductor. Flux will be expelled from the body (shaded region), but not from the hole. It will be maintained by persistent currents in the superconductor. If the magnetic field is switched off, currents will persist and flux will be trapped (Fig.1.11).

F. London suggested that since superconductivity is a quantum phenomenon, the

$$\left(\frac{2\pi\hbar c}{e}\right) = 4\times10^{-7} \quad Gauss\ cm^2.$$

trapped flux should be quantized in units of

This quantity was too small to be measured at that time. Ten years later multiple of half this value was taken as quantum of flux.

1950 Isotope effect

$$T_c \propto \frac{1}{(isotopic\ mass)^{1/2}}$$

Also, $$H_c \propto \frac{1}{(isotopic\ mass)^{1/2}}$$

T_c and H_c are higher for lighter isotopes. This is very significant. So far we have been concerned with electronic behaviour in a superconducter. A superconductor has a lattice of ions and electrons. While the lattice itself does not show any change in properties between the normal and superconducting state, it must nevertheless play a very important role in determining the change in behaviour of the condution electrons.

Considerations of specific heat (Fig.1.12):

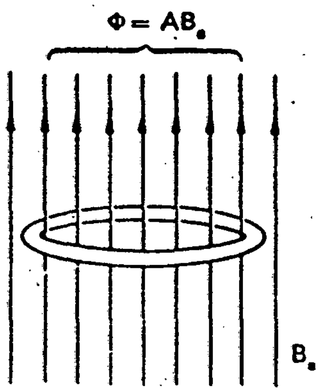


Fig.1.10: Body with a hole in a magnetic field at T > T$_c$.

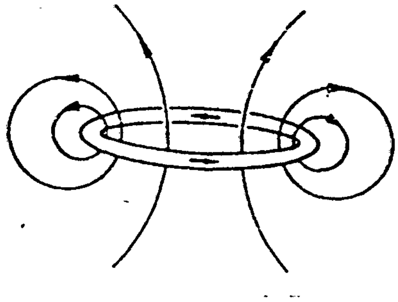


Fig.1.11: When magnetic field is switched off, flux is trapped.

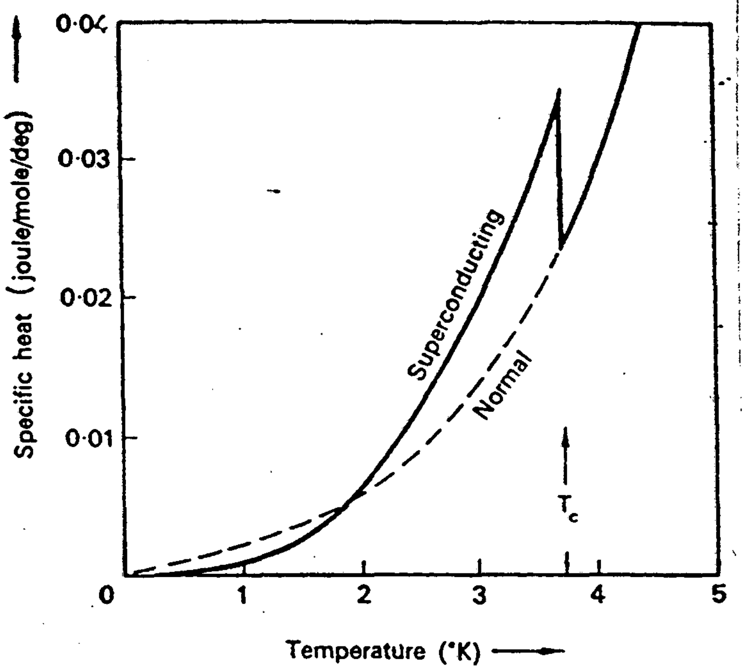


Fig.1.12: Specific heat of tin in normal and superconducting state.

(a) The transition normal to superconducting at T_c is a second order transition (for $H = 0$). Both G and $\frac{\partial G}{\partial T}$ are continuous, while $\frac{\partial^2 G}{\partial T}$ is discontinuous.

(b) The transition when $H \neq 0$, is a first order phase transition. G is continuous but $\frac{\partial G}{\partial T}$ is discontinuous.

(c) Specific heat (normal state) $= A\left(\frac{T}{\theta}\right)^3 + \gamma T$

Where, θ is the debye temperature.

The first term on the RHS represents the contribution of specific heat due to the lattice, while the second term represents the contribution of electrons. The specific heat due to the lattice does not change on the transition from normal to superconducting state.

(d) specific heat due to electrons $\neq \gamma T$ but, $ae^{-b/kT}$.
where, b is the energy gap.

1953 Pippard's nonlocal generalization of London's theory[7]. London's equations are local. 'Local' implies that current densities and electromagnetic potentials are related at the same point in space.

$$\vec{\nabla}\times\vec{J}_s(\vec{r}) = \left(-\frac{c}{4\pi\lambda_l^2}\right)\frac{\vec{\nabla}\times\vec{A}}{\vec{B}(\vec{r})}$$

$$\vec{E}(\vec{r}) \approx \lambda_l^2 \frac{\partial \vec{J}_s(\vec{r})}{\partial t}$$

After a great deal of experimental work, Pippard concluded that these local relations must be replaced by nonlocal relations. Currents at a given point are determined by the space average of field strengths over a region $\approx \xi_0(10^{-4}\text{cm.})$ about the point, where ξ_0 is the coherence length. The experimental evidence is provided by the increse in penetration depth when a superconductor has impurities. Boundary between the normal and superconducting regions is not sharp. n_s changes from 0 in the normal region to its density in the superconducting region (Fig.1.13).

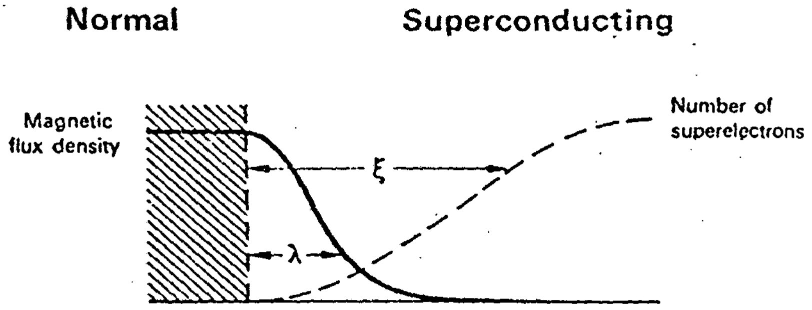


Fig.1.13: Penetration depth and coherence length at boundary.

1954 The first successful superconducting magnet was made by G. B.Yntema at the University of Illions, thereby ushering in the age of engineering superconductivity. Yntema used Nb wire which had been shown by D. Shoenberg at Cambridge University to have a markedly better critical field than any of the other known superconductors. The resulting magnet produced a field of 0.71 T at 4.2 K. He also discovered that cold-working the strands markedly increased the current density that they could carry.

1956 Cooper showed that, in the presense of an attractive interaction between free electrons – no matter how weak – this state becomes unstable[8]. Cooper's work is suggestive of how superconductivity might be arising.

1957 John Bardeen, Leon Cooper, and Robert Schrieffer of the University of Illions at Urbana published their Nobel Prize-winning theory of superconductivity[9]. The superconducting carriers of the phenomenological description are two electrons (Cooper pairs) with equal but opposite momenta and spins. The coherence length is the size of the Cooper pair, and the order parameter is proportional to the electron energy gap, which itself is proportional to T_c. Three years later, Lev Gorkov showed how to unify the phenomenological and microscopic models and to incorporate strong magnetic fields[10]. The key to Gorkov's description was a variation in the energy-gap parameter with position.

1957 Abrikosov investigated if $\xi < \lambda$ in Ginzburg-Landau theory, it would lead to a negative surface energy[11]. Because this behaviour was radically different from the classic behaviour described earlier, he called these 'type II superconductors' (Fig.1.15) to distinguish them from the earlier 'type I superconductors' (Fig.1.14).

1959 Gorkov was able to show that the Ginzburg-Landau theory was in fact a limiting form of the microscopic theory of BCS valid near T_c[12].

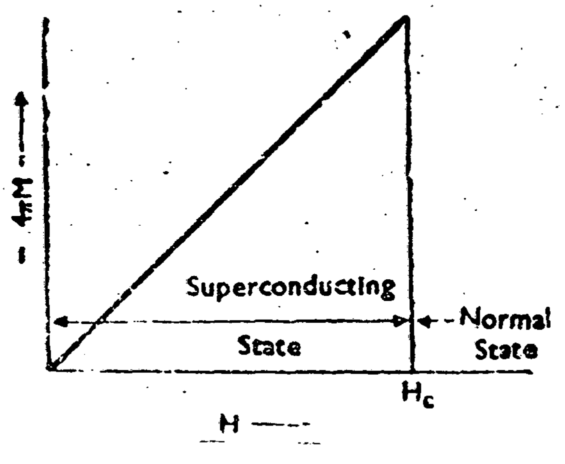


Fig.1.14: Magnetization curve for type I superconductor.

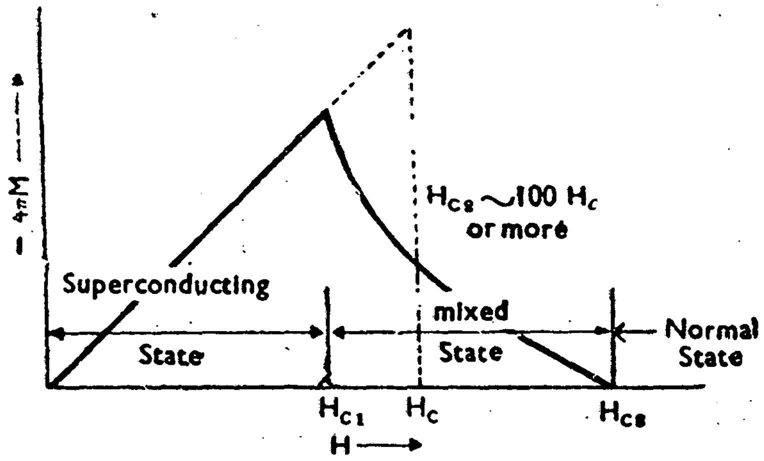


Fig.1.15: Magnetization curve for type II superconductor.

1960 Stan Autler at MIT Lincoln Laboratory produced a 2.5 T field at 4.2 K. Even more significantly, he applied the persistent current in a solenoid to provide the magnetic field for a solid-state maser, perhaps the first application of superconductivity.

1962 One major theoretical advance came in this year, from a gratuate student at Cambridge University, Brian D. Josephson. He predicted that superconducting current would tunnel through a thin insulating layer, or weak link, separating two superconducting electrodes, and that a phase difference would be produced between the superconducting electrons in the two electrodes[13]. The phase difference generates a voltage difference between the two electrodes. The Josephson effect, as it is now known, is the basis for superconducting electronic devices such as the Superconducting quantum interference device (SQUID) and very high-precision voltage standards. It would earn Josephson a Nobel Prize.

1960s & 1970s Much of the theoretical development in these years was in the area of flux pinning. Increasing the critical current density in superconductors reduces costs, because less superconductor is required; it also makes it possible to operate magnets at higher magnetic fields. When current flows through a superconductor it produces a Lorentz force acting to move the flux lines. If the Lorentz force is allowed to move the flux-line lattice freely within the superconductor, then power is dissipated, and eventually the resulting heating may drive the superconductor normal. Introducing microstructural features, such as nonsuperconducting precipitates and grain boundries, that pin the flux lines in place can, however, restrict movement of the flux-line lattice. Understanding the nature of flux pinning is key to understanding how to improve the critical current density in superconductors.

1983 From the late 1960s onwards, the needs of the high-energy physics community propelled considerable advances in superconducting strand technology, initially for bubble-chamber and then for accelerator magnets. In March 1983, the first superconducting accelerator ring was completed at Fermi National Accelerator Laboratory. With 774 dipole magnets 6 m long and 210 quadrupole magnets covering a 4 mi circle, it exemplifies the progress that had been made. The key features were now in place: the superconducting strand was in the required form of a composite of fine (>30 μm diameter) filaments in a high-pyrity, high-normal-conductivity Cu (or Al) matrix for stability, and the strand was twisted in order to reduce filament coupling currents. Superconducting strands were cabled together to form a thick ribbon-like conductor. Increased understanding of the microstructural development of the superconductor and its role in flux pinning would further increase the critical current density, making possible the next generation of accelerators. Four years later, the largest superconducting magnet yet was fabricated for the DELPHI project at the CERN particle accelerator laboratory. The 7.4 m long, 6.2 m diameter, 84 tonne magnet survived a 1600 km trip to CERN by road, ship, and barge.

1986 In April 1986, K. Alex Müller and J. George Bednorz, at the IBM Research Laboratory in Rüschlikon, Switzerland, made a ceramic perovskite of lanthanum, barium, copper, and oxygen that superconducted at 35 K[14]. In fact, small amounts of this material were later found to be superconducting at 58 K due to lead impurities. The impact of this discovery can be gauged by the almost immediate awarding of the Nobel Prize to the two discoverers. The following table brings out the significance of this achievement.

Metal/Compound	T_c	Year
Hg	4.1	1911
Pb	7.2	1913
Nb	9.2	1930
Nb_3Sn	18.1	1954
$Nb_3(Al_{0.75}Ge_{0.25})$	20—21	1966
Nb_3Ga	20.3	1971
Nb_3Ge	23.9	1973

1987 In this year the research groups of Paul Chu at the University of Houston and Maw-Kuen Wu at the University of Alabama at Huntsville substituted yttrium for lanthanum and produced a ceramic that superconducts at 92 K[15]. Now in the space of a year the highest T_c had been raised from 23.9 K (for Nb_3Ge discovered in 1973 by John Gavaler) through 35 K to 92 K, well above the temperature of liquid nitrogen (77 K).

1988 A further huge jump in T_c came in this year from Allen Hermann and Z. Z. Sheng of the University of Arkansas with the discovery of Tl-Ca-Ba-Cu-O superconductor[16] having Tc = 120 K.

1993 In this year A. Schilling, M. Cantoni, J. D. Guo, and H. R. Ott from Zurich, Switzerland, measured a T_c of 133 K in $HgBa_2Ca_2Cu_3O_8$ superconductor[17]. The partial substitution of thallium in this high-T_c mercury-based oxide by P. Dai and B. C. Chakoumakos (Oak Ridge National Laboratory), G. F. Sun and K. W. Wong (University of Kansas), and Y. Xin and D. F. Lu (Midwest Superconductivity Inc.) increased the T_c to138 K for a nominal composition[18] of $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8+\delta}$.

2000 In addition to magnet technology, the high-energy physics community also benefited from superconducting cavity technology. When the Large Electron-Positron Collider was initially run in 1989, with 128 conventional copper accelerating cavities, they provided enough energy to take the energy of each beam to 50 GeV. After upgrading with 272 superconducting cavities, the Large Electron-Positron ring was eventually able to reach 104 GeV per beam in April 2000.

2000 The commercial production of some of the superconductors is quite substantial. In the year 2000 the global demand for Nb-Ti for MRI applications alone was approximately 1000 tons (including the dominant copper fraction), or 60,000 km to 70,000 km (in equivalent length). The estimated value of that demand was about $ 50 Millions.

2001 Magnesium diboride was discovered to be superconductive at a remarkably high critical temperature $T_c = 40$ K for a binary compound. Its high T_c, simple crystal structure, large coherence lengths, high critical current densities and fields, transparency of grain boundaries to current promises that MgB_2 will be a good material for both large scale applications and electronic devices. MgB_2 has been fabricated in various forms, bulk, single crystals, thin films, tapes and wires.

2001-2003 Today superconductors can be found in applications as commonplace as MRI systems installed in thousands of hospitals and cellular-telephone base stations, as well as monumental applications such as particle accelerators. The two major commercial applications are magnetic resonance imaging (MRI), high-field nuclear magnetic resonance (NMR) and superconducting quantum interference devices (SQUIDs). The first 900 MHz NMR has been constructed, with Nb_3Sn superconductor supplying the required field of 21 T. The tau neutrino has been identified at the Fermi National Accelerator Laboratory, near Chicago, using a 4 mi ring of Nb-Ti superconducting magnets. Commercially prouduced cryogen-free receiver subsystems are being installed at an accelerated pace in cellular-telephone base stations. MRI has become both an essential tool of medicine and a key to unlocking the mysteries of the human body. The remarkable flux sensitivity of SQUIDs makes both non-invasive magnetic cardiography and even magnetic encephalography possible. Having once been a fascinating but not particularly useful toy of solid-state physicists, superconductors now make possible the most advanced experiments in chemistry, biochemistry, particle physics, and health sciences. They are also becoming a part of the fabric of modern-day life.

1.3 Scope of the Thesis

In this chapter we discussed the chronology of experimental discoveries and development of theoretical ideas in the field of superconductivity. In the second chapter we shall deal with the applications of superconductivity. This is truly a vast field already, and is expanding further. We shall give a bird's eye view of these applications in different areas, and indicate whether the application is already in use, or is in a stage of development. We also list the applications in greater detail under different heads such as medicine, frequency converters and mixers, infrared detectors, and applications based on the magnetic properties of superconductors, etc. We will also deal with the environmental applications of superconductivity. In the third chapter, we deal with one of these applications, namely the use of superconductivity in transportation. The chapter briefly deals with a history of transportation and is devoted to the evolution of the Maglev (magnetically leviated) concept, leading to the superconducting Maglevs. The fourth chapter deals with the principle of superconducting levitation, the design of guideways and of vehicles. The final section in the fourth chapter is devoted to the state of Maglev in Germany, the U.S., and Japan. In the fifth chapter, taking into account the vastness of the Maglev system and to have a glimpse of it in a simple way, we give a description about Maglev in the form of questions with their answers.

2. APPLICATIONS OF SUPERCONDUCTIVITY

2.1 Introduction

In the previous chapter we discussed the chronology of experimental discoveries and development of theoretical ideas in the field of superconductivity. In this chapter we shall deal with the applications of superconductivity. This is truly a vast field already, and is expanding further. In Sec 2.2, we give a bird's eye view of these applications in different areas, and indicate whether the application is already in use, or is in a stage of development. In the next section, we list the applications in greater detail under different areas such as medical, electronics, industrial, power generation, transportation and thermal. In the final section, we deal with the environmental applications of superconductivity. In this and the preceding section, we give extensive references to enable the reader to follow up any of these applications in detail.

2.2 A bird's eye view of applications of superconductivity

The following table provides the stated perspective.

Area	Application	Current	Emerging
medical	magnetic resonance imaging	X	
	biotechnical engineering		X
electronics	SQUIDs	X	
	transistors		X
	Josephson Junction devices		X
	circuitry connections		X
	particle accelerators	X	

	sensors	X	
Industrial	separation	X	
	magnets	X	
	sensors and transducers		X
	magnetic shielding		X
Power Generation	Motors		X
	Generators		X
	Energy Storage		X
	Transmission		X
	Fusion		X
	Transformers and Inductors		X
Transportation	Magnetically levitated vehicles		X
	Marine propulsion		X

2.3 List of Applications of Superconductivity in greater detail

(1) Medical

(i) Diagnostic Imaging[19,20].

Methods	Information
X-ray Contrast, X-ray computed tomography(CT), electron beam CT, Spiral CT.	Electron density Atomic composition Vascular Lumens
Ultrasound Doppler Ultrasound	Acoustic impedance mismatches Motion
Emission Tomography Positron emission tomography(PET)	Radionuclide concentration (metabolism, recepter densities)

Single photon emission computed tomography(SPECT)	
Magnetic Resonance Imaging(MRI) Magnetic Resonance Spectroscopy(MRS) Magnetic Resonance Angiography(MRA)	Spin density, Relaxation, Diffusion, Chemical composition
Electrical Source Imaging (ESI)	Brain and heart current sources
Magnetic Source Imaging (MSI) Magnetoencephalography (MEG)	Brain Current Sources
Electrical Impedance Tomography (EIT)	Electrical Conductivity
Optical Imaging (Spectroscopy)	Attenuation, Scattering, molecular status

The various methods used for the diagnosis of different body parts and/or diseases are the following.

Brain : X-ray CT, MRI
    Cerebrovascular Diseases : X-ray CT, PET, SPECT
    (Hemorrhage and Stroke)
    Brain Angiography : MRI
    Brain Tumors : X-ray CT, MRI, PET, SPECT
    Brain Neurodegeneration : X-ray CT, MRI
    (Alzheimer's Disease and Multiple Sclerosis)
    Demyelinating Disorders(Multiple Sclerosis) : MRI
Chest (Lung) :
    Lung Cancer : X-ray CT, MRI, PET, SPECT
    Pulmonary Embolism : X-ray CT
Breast Cancer : X-ray mammography, PET, F-18-fluorodeoxyglucose (FDG) tracer, SPECT, Gamma Camera Imaging, Scintimamography.
Heart : Ultrasound, X-ray coronary angiography, MRI, MRA, PET, SPECT
    Coronary Angiography : X-ray
    Coronary Artery Calcification Detection : Electron beam CT
Liver : Ultrasound, X-ray CT, MRI
Colorectal Tumors : X-ray CT, PET
Fetus and Pregnancy : Ultrasound
Female Reproductive Organ Cancer : X-ray CT, MRI
Kidney : X-ray CT, MRI

Prostate : Transrectal Ultrasound, Transrectal MRI
Joint Disease : X-ray CT, MRI
Vertebral Spine Diseases : MRI
Bone Tumors : MRI, X-ray CT
Osteoporosis : X-ray CT, high resolution MRI
Vascular System : X-ray angiography, MRI
Picture Archiving and Communication System (PACS)

(ii) Magnetic Source Imaging

Magnetocardiography (MCG)[21]
Magnetoencephalography (MEG)[22]
SQUID[23]
Study of Brain[24]
Study of Heart[25]

(iii) Magnets for Magnetic Resonance Analysis and Imaging

Nuclear Magnetic Resonance (NMR) : identification of chemical species in weak solution
Superconducting NMR Magnets (Solenoids)[26]
Superconducting MRI Magnets (Solenoids)[27]

(iv) SQUIDs[28]

RF SQUID[29]
dc SQUID
LTS SQUID sensors
HTS SQUID sensors
Magnetoencephalography[30]
Magnetocardiography[21]
SQUID susceptometry[31]
SQUID Magnetometers (Geophysical Applications)[31]

(2) Electronics

(i) SQUIDs[28]

RF SQUID[29]

dc SQUID

LTS SQUID sensors

HTS SQUID sensors

Magnetoencephalography[30]

Magnetocardiography[21]

SQUID susceptometry[31]

SQUID Magnetometers (Geophysical Applications)[31]

(ii) Frequency Convertors and Mixers

Microwave Receivers

Low Noise Superconductor-insulator-superconductor (SIS) Mixer[32]

Superconductor Hot Electron Bolometer (HEB) Mixer[33]

(iii) High Energy Physics Particle Detector Magnets[34]

Thin Superconducting Detector Solenoids[35]

(iv) Infrared Detector Arrays, Uncooled

Bolometric Detectors[36]

Semiconducting Yttrium Barium Copper Oxide (YBaCuO) Microbolometer Arrays[37,38]

Semiconducting YBaCuO Pyroelectric Detectors[39]

Lead Titanate-based Detectors

Barium Strontium Titanate Pyroelectric Detectors

(v) Microwave Ferroelectric Devices

Varactors

Oscillators

Tunable filters[40]

Phase shifting devices

(vi) Superconducting Magnets for Particle Accelerators and Storage Rings

Tevatron[41]

HERA[42]

UNK[43]

SSC[44]

RHIC[45]

LHC[46]

(vii) Cyclotrons

Superconducting Cyclotrons[47]

Compact Synchrotron Light Sources[48]

(viii) Magnetic Sensors[49]

Inductive Sensors

Eddy Current Sensors

Transformative Sensors

MOS Magnetic Field Sensors

Magnetometers

SQUID Magnetometers

Magnetoresistive Sensors

Hall-effect Sensors

Magneto-optical Sensors

Magnetic Thin Films

(ix) Superconducting Cavity Resonators

TeV electron-positron linear collider[50]

multi-TeV muon collider[51]

(x) High-temperature Superconducting Film Processing Technology[52]

Passive Superconducting Microwave Device[53]

High Temperature Superconducting Filters[54]

High Temperature Superconducting Delay Lines[54]

(3) Industrial

(i) Magnetic Seperation

High Gradient Magnetic Seperation[55]

Low-Temperature Superconducting Solenoid Electromagnets[56]

High-Temperature Superconducting Solenoid Electromagnets[57]

LTS Reciprocating Magnetic Seperator[58]

HTS Reciprocating Magnetic Seperator

Ore Seperation

- Kaolin Processing
- Titanium Dioxide Processing
- Chemical Processing[59]
- Water Treatment[60]
- Solid Waste Remediation[61]
- Coal Purification

(ii) <u>Magnetic Sensors</u>[49]

- Inductive Sensors
- Eddy Current Sensors
- Transformative Sensors
- MOS Magnetic Field Sensors
- Magnetometers
- SQUID Magnetometers
- Magnetoresistive Sensors
- Hall-effect Sensors
- Magneto-optical Sensors
- Magnetic Thin Films

(iii) Hall Effect Transducers[62]

<u>(4) Power Generation</u> [63]

(i) Energy Storage

- Supercapacitors[64]
- Power Quality[65]
- Microsuperconducting Magnetic Energy Storage[66]

(ii) Transmission

- Superconducting Fault Current Limiters[67]
  (in electrical transmission and distribution networks)

(iii) Superconducting Magnets for Fusion Reactors[68]

- Mirror Devices[68]
- Tokamaks[69]
- Stellarators[70]

  - Magnetic Mirror Confinement[71]
  - Gyrotron[72]

(iv) Superconducting Transformers[73,74]

<u>**(5) Transportation**</u>

(i) Superconducting Levitation[75]

(ii) Superconducting Bearings (for flywheel energy storage)[76]

(iii) Marine propulsion

(iv) Space craft launching

<u>**(6) Thermal**</u>

(i) <u>Temperature Sensors</u>[77]

  - Resistance Sensors
  - Semiconductor Sensors
  - Thermocouple Sensors
  - Quartz Temperature Sensors
  - Radiation Thermometry[78]

(ii) Thermoelectric Conversion (Heat→Electric Power)

  - Thermoelectric power generation[102]
  - Thermoelectric refrigeration[103]

(iii) <u>Peltier Effect</u>[104]

  - Peltier Refrigeration
  - Peltier Refrigeration in the millikelvin temperature range

2.4 Environmental Applications of Superconductivity

Many large scale industrial applications of superconductivity which have the potential of impact on the environment, are either in use or in the stage of development for use. These can be classified in various ways; for example, one could categorize applications in terms of the superconductors characteristic behaviour, i.e. Type1, Type2, ac, dc etc. Perhaps the most useful classification, however, is in terms of the end use. Table1 lists the major applications as to end use.

There are, of course, many other possible applications: instruments, computers, electron microscopes etc. These applications will probably be significantly less important in terms of overall use and impact on the environment.

Table 2.1

Large Scale Applications of Superconductivity having Potential of Impact on Environment

(1) Energy Production	Fusion MHD (Magnetohydrodynamic)
(2) Energy Storage	Magnetic
(3) Energy Transformations	AC Generators and Motors[105] DC Generators and Motors Transformers
(4) Energy Transmission	AC Cables DC Cables
(5) Transportation	High Speed Ground Transport (Passenger and/or Freight) Space Craft Launch
(6) Industrial Processing	Seperation (Ore, Recycling) Water Filteration Effect on Chemical, Metallurgical Reactions

An interesting aspect of the applications in Table2.1 is that several alternative commercial methods not using superconductivity now commercially exist for each area, and advanced methods, again not using superconductivity, are being developed. Thus, if superconductivity is to be applied in a given area it, and the system it is part of, must offer significantly better performance and/or costs than alternative methods. Many facters affect whether or not the above applications prove feasible. These factors are:

(1) advances in superconductor technology
(2) development of the required superconducting components
(3) economic practicality of the application
(4) technical feasibility
(5) esthetics
(6) political and social factors
(7) reliability and safety of superconducting systems
(8) capital investments

These are some of the many factors that will ultimately decide whether or not a given application will be successful. Some factors are quantitative, but are not well known, and some are qualitative and very intangible. Predictions of ultimate success for any given application are thus very subjective. Table2.2 attempts to summarize an assessment, given by J. Powell, of the chances for success of the various applications, based on technical factors (field capability, degree of losses, stability); economics; problems of other system components; and intangible factors.

Table 2.2

Assesment of Large Scale Superconductor Applications

Capability of Current Superconductors
and Cryogenic System to Meet Desired Application

Application	Field	Losses	Stability	Projected cost of Superconducter and Cryogenic system	Probability of significant Application
(1)Fusion (dependent on confinement method)	G-P	G-P	G-P	G-P	VG
(2) MHD	G	G	G	VG	F to G
(3) Magnetic Storage	G	G	G	F to G	F to G
(4) AC Gen. & Motors	G	G	G	G	G
(5) DC Gen. & Motors	G	G	G	G	G
(6) Transformers	G	P	F	P	P
(7) DC Transmission	G	G	G	F	F to G
(8) AC Transmission	G	F	G	F	F to G
(9) High Speed Train	G	F	G	G	G
(10) Ore Seperation	G	G	G	G	G

VG—Very Good ; G—Good ; F—Fair ; P—Poor.

3. MAGLEV FOR TRANSPORTATION

3.1 Introduction

Even though the myriad applications briefly mentioned in the previous chapter ultimately depend upon the two fundamental properties of a superconductor, viz. zero resistance below the critical temperature and perfect diamagnetism below the critical field, the necessary technology to make any of these applications work is a complicated affair. Therefore, to be able to discuss it in some length, we have chosen to deal here with one of these applications, namely the use of superconductivity in transportation. The chapter is organized as follows. Sec 3.2 briefly deals with a history of transportation. Sec 3.3 is devoted to the evolution of the Maglev (magnetically leviated) concept, leading to the superconducting Maglevs. The stage is thus set to deal with the principle of superconducting levitation in the next chapter.

3.2 History of transportation[79,86]

The following table brings out the significance of the history of transportation:

History of Transport	
Mode	Introduction
Bipedalism	2 million years BC
Ships	50,000 years BC
The Wheel	5000 years BC
Railroads	Early 1800s
Autos, Trucks and Buses	Early 1900s
Rockets	1940s
Maglev	1960s

3.3 Evolution of the Maglev

3.3.1 Introduction[87-91]

The most recent new transport mode is maglev. The goal of using magnets to achieve high speed travel with non-contact magnetically levitated vehicles is almost a century old. In the early 1900's, Bachelet in France and Goddard in the United

States discussed the possibility of using magnetically levitated vehicles for high speed transport. However, they did not propose a practical way to achieve this goal.

In 1966, Powell and Danby proposed the first practical system for magnetically levitated transport, using superconducting magnets located on moving vehicles to induce currents in normal aluminum loops on a guideway. The moving vehicles are automatically levitated and stabilized, both vertically and laterally, as they move along the guideway. The vehicles are magnetically propelled along the guideway by a small AC current in the guideway. The original Powell-Danby maglev inventions form the basis for the maglev system in Japan , which is currently being demonstrated in Yamanashi Prefecture, Japan. Powell and Danby have subsequently developed new Maglev inventions that form the basis for their second generation M-2000 System.

Maglev promises to be the major new mode of transport for the 21st Century. Because there is no mechanical contact between the vehicles and the guideway, speeds can be extremely high. Traveling in the atmosphere, air drag limits vehicles to speeds of about 300 mph. Traveling in low pressure tunnels, maglev vehicles can operate at speeds of thousands of miles per hour. The energy efficiency of Maglev transport, either in kilowatt-hours per passenger mile for personal transport, or kilowatt hours per ton-mile for freight, is much lower for maglev than for autos, trucks, and airplanes. It is pollution free, can use renewable energy sources such as solar and wind power, and in contrast to oil and gas fueled transport, does not contribute to global warming. It is weather independent, and can carry enormous traffic loads - both people and goods - on environmentally friendly, narrow guideways. The cost of moving people and goods by maglev will be considerably less than by the present modes of auto, truck, rail, and air.

In addition to dramatically improving transport capabilities on Earth, maglev has the potential to greatly reduce the cost of launching payloads into space. While it presently costs $10,000 per pound to orbit payloads using rockets, the energy cost to orbit that same pound would be only 50 cents per pound, if it were magnetically accelerated to orbital velocity. As ultra high velocity magnetic launchers are developed, the cost of reaching space will come down to everyday, mass market standards.

These and additional maglev applications such as maglev for mining, the Water Train and others will hold an important place in transportation history.

3.3.2 Types of maglev[87-92]

All practical maglev systems have powerful magnets mounted on the moving maglev vehicle. The magnets interact with a normal temperature guideway, generating magnetic forces that stably levitate the moving vehicle. Besides levitating the vehicle, the magnetic forces must counteract all external forces on the vehicle, such as head, tail, or cross winds, up and down grades, curves, misalignment or guideway loops, etc.

An important goal for maglev designers is to minimize the cost of the maglev system, so that it competes economically with other modes of transport. Of course, minimizing cost is only one goal. Other goals are safety (the primary goal), environmental friendliness, the capability to carry many kinds of heavy loads, operational simplicity and reliability, ability to operate in all weather conditions, ability to use existing rights of ways, and the capability to operate intermodally with other modes of transport.

Of the various maglev possibilities, systems based on superconducting magnets best achieve the above goals. Prior to Danby and Powell's invention of superconducting maglev, three types of maglev had been considered :

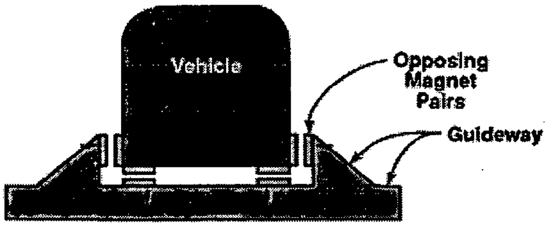
(a) Permanent magnets on the vehicle and guideway

(b) Electromagnets on the vehicle and an iron rail guideway

(c) Alternating Current coils on the vehicle and conducting sheets on the guideway

3.3.3 Permanent magnet maglev

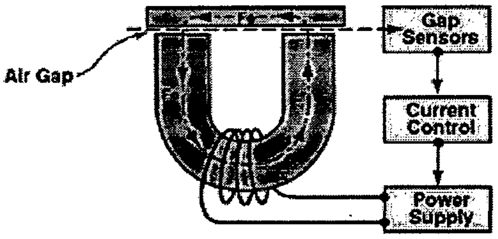
Permanent magnets are positioned along each side of the maglev vehicle. These magnetically interact with permanent magnets on the guideway to provide levitation and lateral guidance. The magnetic polarities of the vehicle and guideway magnets generate repulsive magnetic forces that suspend the vehicle and push it toward the center of the guideway. The suspension automatically opposes any external force (wind, grades, curves, etc.) that tries to displace the vehicle from its equilibrium position.



Magnetic Suspension Based On The Repulsive Force Between Permanent Magnets On A Vehicle

Small-scale permanent magnet maglev vehicles have been built and operated. However, for practical, long distance transport systems, permanent magnets are not practical. The cost of permanent magnet guideways is too great. Moreover, the clearance between the vehicle and the guideway is a fraction of an inch. The cost of constructing a guideway to the requisite tolerances, its vulnerability to foreign objects (trash, wind borne debris, etc.) and the problems of ice and snow buildup, make it impractical for high speeds travel.

3.3.4 Electromagnet maglev[93-94]



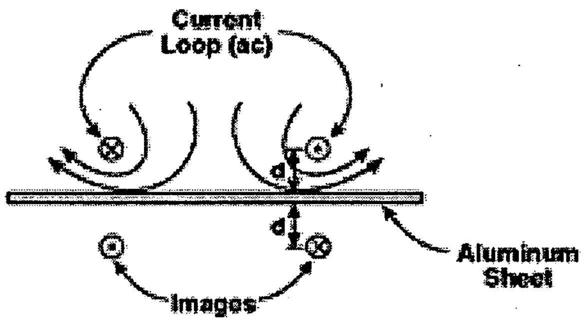
Magnetic Suspension Based On Servo Control Of The Attractive Force Between An Electromagnet And A Ferromagnetic Sheet

The electromagnetic suspension was, proposed by Graeminger in the 1930's. In the 1970's, Germany started development of this approach, which has resulted in the Transrapid System (see Maglev in Germany). The suspension is inherently unstable because, as the gap between the electromagnet and the iron sheet decreases, the attractive force increases. However, the suspension can operate stably by continuous servo control of the winding current in the electromagnet. If the gap between the vehicle electromagnet and the guideway iron sheet above it decreases, the current in the winding on the electromagnet is reduced, reducing the attractive force. If the gap between increases, the current is increased. This current is servo controlled on a time scale of a few thousandths of seconds.

Although the electromagnet approach eliminates the high cost of permanent magnets on the guideway, the problem of very small gap between the vehicle and the guideway remains. In the Transrapid System, the gap is 3/8th of an inch. Because of the narrow gap, the guideway construction and maintenance tolerances are extremely tight which substantially increases cost. In addition, ensuring adequate clearance under various environmental challenges, such as ice and snow buildup, earth settling, earthquake movements, and thermal expansion due to temperature changes is difficult.

3.3.5 Conducting sheet maglev[87, 95-99]

The third approach, levitation by the magnetic interaction between an alternating current (AC) coil and the induced currents in a conducting sheet, was proposed by Bachelet in 1912. This suspension, like the permanent magnet suspension, is inherently stable. If the gap between the AC coil and the conducting sheet decreases, the magnetic repulsive force increases, pushing the coil back up to its equilibrium height. If the gap increases, the magnetic force decreases, causing the coil to move downwards to its equilibrium point. The suspension is vertically stable.



Magnetic Suspension Based On The Repulsive Force Between A Coil Carrying Alternating Current (ac) And A Conducting Sheet.

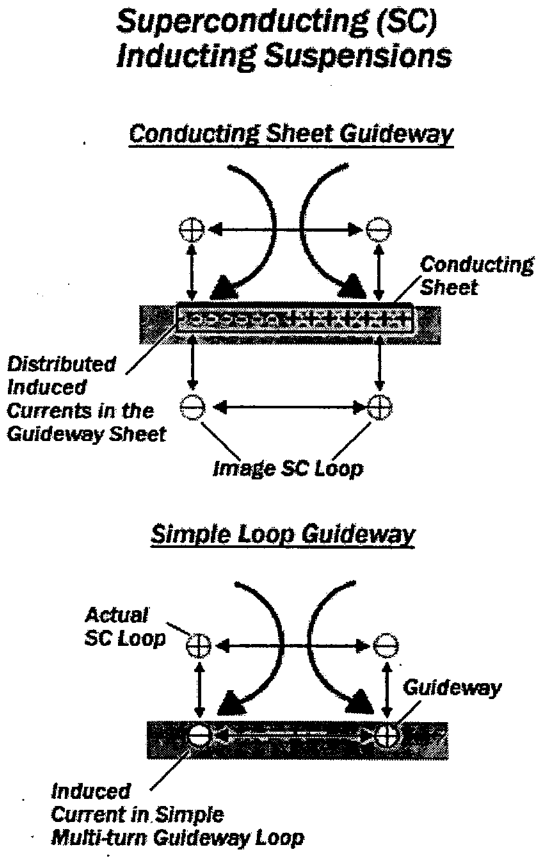
Side plates can be incorporated in the guideway to make the suspension laterally stable as well.

Although inherently stable, the power losses in the AC coil and guideway are too great for this approach to be practical.

In 1966, Powell and Danby, realizing that the above approaches were not practical, proposed a new concept based on the use of superconducting magnets on the vehicle. They reasoned that superconducting magnets, which can be made very powerful in terms of their magnetic field strength, lightweight, and essentially lossless (except for a small power input to the cryogenic refrigerator), could levitate vehicles that moved along a guideway of conventional room temperature conductors.

3.3.6 Modern superconducting maglev[87-90]

In effect, the superconducting magnets behave like extremely powerful and lightweight permanent magnets. As the vehicle moves, its magnets induce currents in the guideway conductors, generating a magnetic repulsive force that levitates the vehicle. The levitation is automatic and inherent as long as the vehicle is moving, and is inherently and passively stable. If the gap between the vehicle and the guideway decreases, the levitation force on the vehicle increases, automatically pushing it away from the guideway.



The simple conducting sheet guideway has a large magnetic drag force because the induced currents in the guideway are comparable to those in the superconducting magnets on the vehicle. While the vehicle magnets are lossless, the induced currents in the normal conductors on the guideway are not, and produce power losses, which result in a magnetic drag force on the vehicle.

Realizing this, Powell and Danby focused on maglev designs that minimize the magnitude of the induced currents in the guideway relative to the superconducting currents in the vehicle magnets. This in turn minimizes the losses in the guideway and the resultant magnetic drag on the vehicle.

In their first maglev design, Danby and Powell proposed having a sequence of simple conductor loops in the guideway, instead of a conducting sheet. For a given magnetic levitation force, this configuration has considerably lower power losses and magnetic drag forces than the simple conducting sheet guideway.

Following their initial design, Powell and Danby then developed even higher performance maglev configurations, as described in the Principle of Levitation.

4. SUPERCONDUCTING MAGLEV

4.1 Introduction

The evolution of the concept of the modern superconducting maglev was traced in the last chapter. We deal here in some detail with the principle of levitation (Sec 4.2), the design of guideways (Sec 4.3) and of vehicles (Sec 4.4). The final section in this chapter is devoted to the state of Maglev in Germany, the U.S., and Japan.

4.2 Principle of levitation[83, 100-101]

4.2.1 Two key inventions

As the pioneers of superconducting maglev, Powell and Danby made two basic inventions that have been key to its development:

(a) The Null Flux Suspension

(b) The Linear Synchronous Motor (LSM)

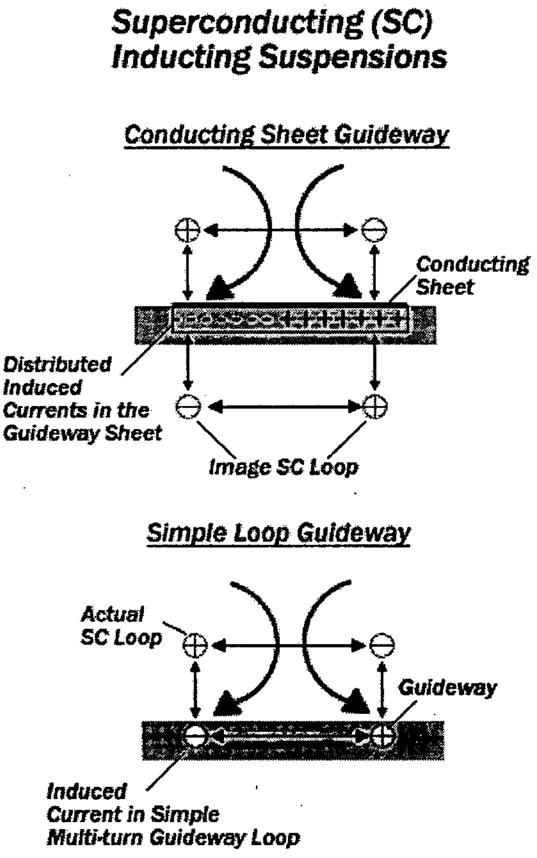
The Null Flux suspension makes the power losses in the guideway from the induced currents in normal metal loops very low. As a result the magnetic drag force on the vehicle is small. In fact, it is much smaller than the air drag force. This is important because maglev vehicles then need much less energy per passenger mile and ton mile than other modes of transport. Moreover, the Null Flux suspension also is inherently and passively stable, and strongly counteracts all external forces (winds, up and down grades, curves, etc.) that try to push the vehicle away from its equilibrium point.

Because the levitated vehicle does not contact the guideway, conventional propulsion cannot be used. Instead, maglev vehicles are magnetically propelled by the highly efficient Linear Synchronous Motor (LSM). In the LSM, a small alternating current in a second set of guideway loops (the LSM propulsion loops are distinct from the loops that levitate and stabilize the maglev vehicle) magnetically push on the superconducting magnets, propelling the vehicle along the guideway.

The superconducting magnets on the vehicle are DC (Direct Current) magnets - that is, their magnetic fields do not vary with time. However, the magnetic polarity -that is, the direction of the magnetic field- of the magnets alternates along the vehicle. Accordingly, the guideway loops experience an alternating wave of magnetic flux as the vehicle moves past. A downwards magnetic flux is followed by an upwards flux, then by a downwards flux, and so on.

4.2.2 Null flux suspension

The induced current in the guideway loop or sheet is opposite in direction to the current in the superconducting magnet on the vehicle, producing a magnetic levitation force. As the next vehicle magnet passes over the loop or sheet, the direction of the induced current changes in accordance with the change in magnet polarity. However, the magnetic force remains in the upwards direction, and continues to levitate the vehicle.



The frequency of the alternating magnetic flux wave is determined by the vehicle speed. At normal operating speed, the frequency is high enough that the induced currents in the guideway loops do not significantly decay due to their electrical resistance.

In the Null Flux suspension, the guideway loops are wound in a configuration that reduces their induced current to a much smaller value than is possible for the sheet or simple loop configuration. Because the induced current is much less, the resistance losses are very low, making the magnetic drag force on the vehicle very small.

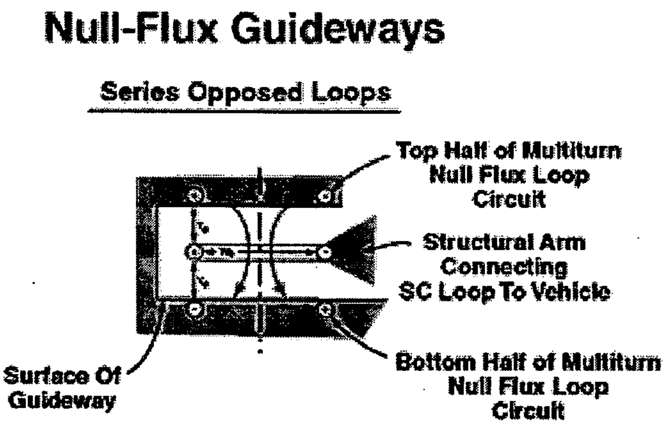
4.2.3 Null flux geometries[83]

There are many geometric forms of Null Flux guideway loops. All of the various geometries share a common feature. The null flux guideway loop is wound so that when the vehicle is at the symmetry point of the loop, the net magnetic flux through the loop circuit is zero. Since the net magnetic flux is zero, the induced current in the loop is also zero.

If the vehicle magnet moves away from the symmetry point in any direction, the magnetic flux through the loop circuit becomes non-zero, causing an induced current to flow in the loop circuit.

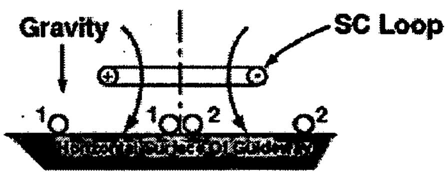
The direction of the induced current is always such that the resultant magnetic force acts to push the vehicle magnet back towards the symmetry point.

When the superconducting (SC) loop on the vehicle is exactly halfway between the upper and lower halves of the null flux guideway loop circuit, the net flux through the circuit is zero, because the top half loop is wound in the opposite direction from the bottom half loop. (The + and - signs in the guideway loop circuit indicate the winding direction).



If the vehicle SC loop moves downward from the center symmetry point of the null flux guideway loop, an induced current and magnetic force develop so as to push the vehicle loop upwards. If the vehicle loop moves upwards, an induced current and magnetic force develop so as to push the vehicle loop downwards.

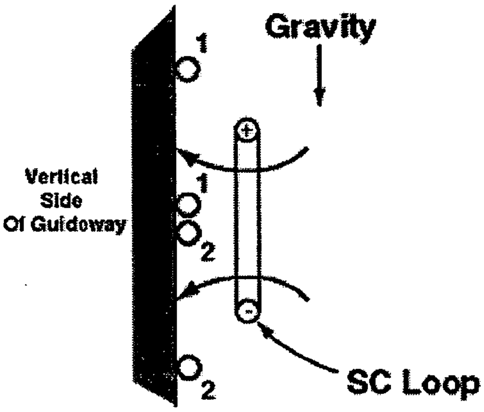
Horizontal Figure Of 8



#1 and #2 Loops wound in opposite directions and coupled to form a complete circuit

In an actual maglev system where the vehicle has a non-zero weight, the vehicle SC loop rests at a stable position slightly below the symmetry midplane. At this position, the induced current in the null flux guideway circuit generates a magnetic lift force that equals the downwards weight of the vehicle. Any external force that tries to move the vehicle away from this suspension point is automatically countered by a change in the induced current and magnetic lift force.

Vertical Figure Of 8



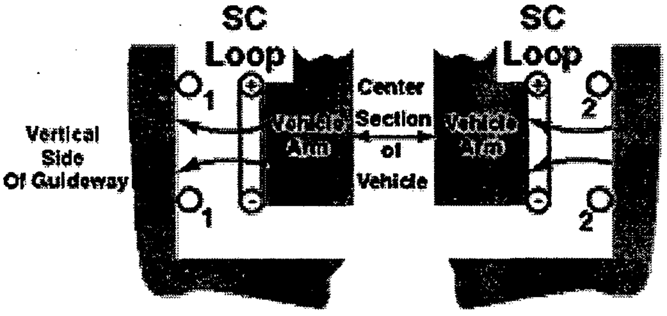
The null flux configuration permits the use of much stronger superconducting magnets in the vehicle than are possible using a conducting sheet or simple loop guideway. As a result, for a given magnetic levitation force, the induced current in the null flux loops is much smaller than for a conducting sheet or simple loop guideway. This greatly reduces the power losses in the guideway.

The same null flux principle applies to the "Figure of 8 loop." When the vehicle SC loop is centered on the "Figure of 8 loop," the net magnetic flux through the "Figure of 8" loop circuit is zero. If the SC loop moves to the left or right, a net magnetic flux results, inducing a current that pushes the SC loop back to its centered position.

The "Figure of 8 loop" is laid on the horizontal surface of a planar guideway and provides a horizontal restoring force if the vehicle is subjected to an external horizontal force, i.e., a cross wind. The "Figure of 8 loop" can also be vertically oriented. In the vertical orientation it provides both vertical lift and a vertical restoring force to the equilibrium suspension point. The vertical "Figure of 8" configuration is used on the side walls of the Japanese maglev U-shaped guideway.

Still another null flux configuration is formed by connecting the #1 and #2 guideway loops on the sidewalls of a U-shaped guideway. When the maglev vehicle is centered between the null flux loops, the net magnetic flux and current in the null flux circuit are zero. If an external force tries to push the vehicle either left or right, a net current and horizontal magnetic force develops in the null flux circuit pushes the vehicle back to its centered position.

Cross-Coupled Lateral Loops



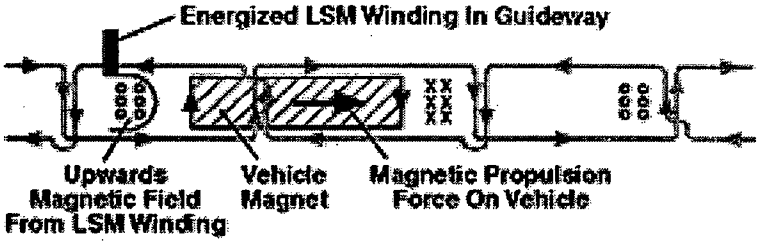
#1 and #2 Loops wound in opposite directions and coupled to form a complete circuit

Using the null flux suspension, the magnetic drag force on the vehicle can be made much smaller than the air drag force. At 300 mph, the air drag force is typically about 5 to 10% of the vehicles weight, while the magnetic drag force is about 1 % or less.

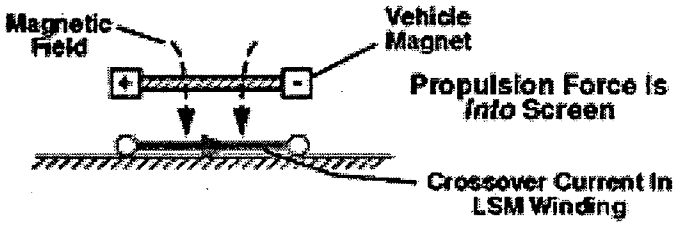
4.2.4 LSM propulsion

The second key invention of Drs. Powell and Danby is the Linear Synchronous Motor (LSM). The guideway has a set of LSM windings that carry a small alternating (AC) current, e.g., several thousand amp turns. The AC current is supplied from a conventional electrical power grid. When energized, they produce a traveling magnetic wave that pushes on the vehicle, overcoming whatever drag forces are acting on it. In effect the vehicle "rides" the AC LSM wave much as a surfer rides a water wave. It moves at the same speed as the LSM wave. The speed is determined only by the frequency of the AC power fed into the guideway. The maglev vehicles maintain a constant separation distance between them regardless of variations in head or tail winds, up or down grades, etc. acting on individual vehicles. Constant separation is very important for safety. The vehicle is easily controlled by adjusting the frequency of the LSM AC power wave.

LSM Top View

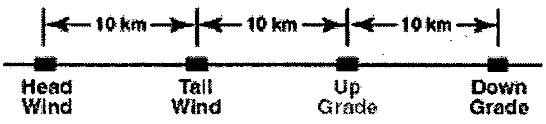


LSM End View

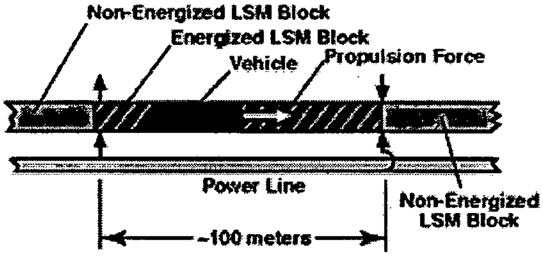


High energy efficiency of the LSM propulsion system is achieved by not continuously energizing the entire guideway. Instead, only the local block of guideway on which the vehicle travels is energized. The length of the energized block is typically several hundred feet. When the vehicle leaves the energized block, LSM power is electronically switched to the next block and the old block is switched off. In this mode, LSM efficiency (propulsion power/input electric power) is over 80%.

Constant Separation Distance



Energized LSM Block Operation



4.3 Guideways

As described earlier, the narrow beam guideway has two sets of panels, one on each side of the beam. The beam is a hollow box structure of reinforced, pre or post tensioned concrete. Outer dimensions are 70 feet in length, 4 feet in width, and 5 feet in height.

Each panel holds wound aluminum conductor loops. A typical panel loop assembly contains 3 different kinds of loops. The Figure of 8 null flux loops levitate the vehicle and vertically stabilize it. The long dipole loops provide LSM propulsion. The short dipole loops on the sides of the beam form a null flux circuit that horizontally stabilizes the vehicle.

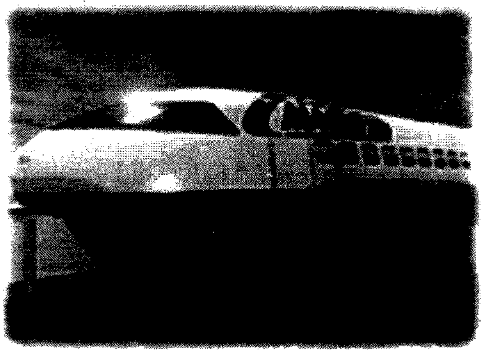
The Figure of 8 and short dipole loops are discrete and not connected to their neighbours. The LSM loops connect to form a continuous electrical circuit, that runs the full length of the beam. Adjacent beams are connected to form the energized block. (The nominal block length is 4 beams.)

The loop assembly is encased in concrete to form a finished panel with outer dimensions of 10 feet in length, 40 inches in width, and 3 inches in thickness. The panels are attached in the factory to the narrow beams before they are shipped to the construction site.

The M-2000 planar guideway uses the same panels except that they are laid in two lines along the guideway. In the planar guideway, the Figure of 8 loops laterally stabilize the vehicle. The LSM long loops provide propulsion, and the short dipole loops levitate and vertically stabilize the vehicle. However, they are not connected as a null flux circuit, but operate as simple loops.

4.4 Vehicles

The M-2000 passenger vehicle cabin dimensions are similar to a mid-size jet airliner like the MD-80. Unlike airliners, however, all passengers on M-2000 vehicles enjoy first class seating with ample leg room and wide, comfortable seats. The M-2000 guideway also transports freight vehicles. The trailer would roll onto and off the Maglev vehicle in two minutes, similar to trailers carried by the Chunnel Trains. M-2000 freight vehicles can also transport containerized freight.



Depending on traffic density, M-2000 vehicles operate individually or as multi-car "train sets." Headways of 1 minute are practical (5 miles separation between vehicles). An M-2000 two-way guideway with single vehicles can carry 12,000 passengers or 120 trailer trucks per hour. With three vehicle "train sets," the capacity would increase by a factor of 3. Multi-vehicle sets operate at peak traffic periods, and single vehicles at off-peak. A 2-way M- 2000 guideway could carry 100,000 passengers and several thousand trailer trucks daily. At 10 cents per passenger-mile and 20 cents per ton-mile, revenues would be 6 million dollars per mile of guideway per year. This would payback the 10 million dollar per mile capital cost of a 2-way M-2000 guideway in a couple of years.

Features of M-2000 Maglev Vehicles

Passenger Vehicles

- 100 person capacity
- First class seating accommodations
- 110 foot vehicle length
- 11 foot vehicle width
- 300 miles per hour maximum speed

Freight Vehicles

- Can carry 80,000 pound trailer
- 16 foot internal clearance
- 60 ton vehicle weight
- 100 vehicle length
- 12 foot vehicle width
- 300 miles per hour maximum speed
- Can also transport freight containers

4.5 Current Status of Maglev

4.5.1 Introduction

First generation maglev systems have already been developed in Japan and Germany; while a second generation system with enhanced performance capabilities is being developed in the United States. Within the next few years these Maglev systems will be built and operating in the US and other countries. Our existing modes of transport have served us well, in the past, but fall short of meeting our transport needs in the 21st Century. Maglev can move people and goods with much greater mobility and speed, using much less energy, at lower cost, and with greatly reduced pollution, compared to the existing modes of transport.

4.5.2 Maglev in the U.S.A.[81,82]

(a) the next generation: First generation maglev systems have been demonstrated in Japan and Germany. The Japanese maglev system, which is based on the original superconducting maglev inventions pioneered by Drs. Powell and Danby[83], has been very successful. The Maglev 2000 of Florida Corporation is developing a second generation maglev system that is based on the recent maglev inventions of Drs. Powell and Danby. This

Advanced Performance Capabilities of the M-2000 Maglev system

- Guideway carries both passengers and freight vehicles
- Vehicles can travel on either narrow beam or planar guideways and transition from one to the other
- Vehicles can electronically switch at 300 miles per hour to off-line stations
- Low guideway capital cost (~10 million dollars per two-way mile)
- Magnetic fields in the passenger compartment are at Earth ambient level

second generation system has improved performance capabilities and reduced costs. Maglev 2000 plans to build the first US maglev system in Central Florida. Technical details of the M-2000 system are described in principle of levitation. A key feature of the M-2000 System is the use of superconducting quadrupole magnets on the maglev vehicles. The quadrupole configuration enables the M-2000 vehicles to travel on low cost narrow beam guideways, and to smoothly transition to a flat planar guideway whenever it is desired to be able to switch the vehicle to a second guideway. This switching can take place at high speed, i.e., 300 mph, without having to slow the vehicle down. The switching process is electronic and does not require mechanical movement of a section of the guideway.

(b) high-speed switching: The ability of M-2000 vehicles to switch at high speeds allows them to maintain high average speed, while having many stations connected to the maglev system, because they do not have to slow down on the main guideway if they are going to switch off.

Accordingly, the M-2000 vehicles can operate in a "skip-stop" fashion, bypassing off-line stations at high speed that they are not scheduled to stop at. For these stations when the vehicle is scheduled to stop, it would switch off the main guideway at high speed onto a secondary guideway, on which it would decelerate to stop at an off-line station. After unloading and loading, the vehicle would leave the station, accelerating up to cruise speed, and be switched back onto the main guideway.

M-2000's high speed switching capability enables its maglev vehicles to efficiently serve the highly dispersed US population with many maglev stations, rather than having only a few stations located in large urban centers. The majority of the US population would live within a few miles of a maglev station, is which they would have ready access. Once at the station they would be able to travel to virtually any metropolitan region in the US, to reach the station within a few miles of their destination.

(c) the path to profitability M-2000's ability to transport trailer trucks as well as passengers on the same guideway is the key to making maglev a low cost, nationwide mode of transport in the United States. The US currently spends over more than 260 billion dollars annually on intercity truck transport, over 4 times as much as it spends on intercity air passenger transport. Using the M-2000 system, a tractor from the trucking company would pick up a trailer at its origin point and drive it to the nearest maglev station. From there, the trailer would be transported hundreds of miles on a M-2000 maglev vehicle to the station nearest its destination, where it would be picked up by a second tractor and delivered to the destination. The trailer transport vehicle could also carry freight containers, if desired.

The revenues from transporting 2000 trailers per day - a small fraction of the daily truck traffic on many of the US Interstates - are equivalent to carrying 100,000 passengers per day, which far exceeds any intercity traffic load in the United States. By carrying trailer trucks the payback time for an M-2000 intercity maglev system can be cut to as little as 3 years, compared to the 30 or more years it would take if the system only carried passengers.

Maglev2000 is planning a 20 mile Maglev route in central Florida that would connect Port Canaveral to the regional airport in Titusville, with an intermediate station at the Visitor Center in the Kennedy Spaceport. Almost 3 million passengers per year take cruise ships from Port Canaveral and a comparable number go to the Kennedy Visitor Center. By transporting passengers to the Port and the Visitor Center, a maglev system would lessen congestion and delays and reduce pollution. The number of people visiting these points is steadily increasing, and will probably double within a decade. The substantial ridership, and the environmental benefits, make this route an excellent candidate for the first US maglev system.

4.5.3 Maglev in Japan[84]

A first generation superconducting maglev system is now operating in Japan. The system, which has been developed and built by Japan Railways, is located in Yamanashi Prefecture north of Mt. Fuji. Japan's system, and is based on the original maglev inventions of Drs. Powell and Danby[83]. The 20 kilometer long, 2-way guideway system has succeeded in demonstrating the feasibility and advantages of maglev.

The Japanese vehicles are full size, commercial type maglev vehicles that run on the JR (Japan Railways) u-shaped guideway. Speeds of up to 350 mph have been achieved.

Intermodalism - that is, the capability to transfer easily and efficiently between different modes of transport - is very desirable. Because it can easily adjust to virtually any type of terrain, and can use existing rights of way, maglev is highly intermodal. Stations can be readily located adjacent to highways, airports, seaports, and rail stations.

Following the completion of their maglev test program at Yamanashi, Japan Railways will decide on whether to proceed with the planned 300 mile Tokyo to Osaka maglev system. Approximately 60% of the route will be in deep tunnels, traversing the central mountainous region of Japan. Maglev "trains", consisting of up to 14 vehicles attached together, will make the 300 mile trip in approximately one hour.

Japan Railways has also developed a mechanical switch for maglev guideways. The switch, must operate at low vehicle speeds, because of length limitations. To switch from one guideway line to another at high speed requires very long switch sections, hundreds of meters at 300 mph for example. In contrast, the M-2000 electronic switch can easily switch vehicles traveling at 300 mph.

Japanese Maglev Achievements:

- Full size, commercial type vehicles
- Vehicle speeds up to 350 MPH
- Vehicle/guideway clearances of 4 inches
- Operation of multiple vehicle train sets
- U-shaped guideway with Null Flux levitation loops
- Magnetic propulsion by Linear Synchronous Motor
- High speed operation in deep tunnels
- Low speed mechanical switches

4.5.4 Maglev in Germany[85]

A different type of first generation maglev system, termed Transrapid, is presently operating in Germany. Instead of using superconducting magnets on the maglev vehicle, the German system uses conventional, room temperature electromagnets. The electromagnets are located on each side of the vehicle, and run along its entire length. These electromagnets are magnetically attracted upwards to iron rails positioned under the edges of the guideway structure. The magnetic lift force then levitates the vehicle.

Since the attractive force between the vehicle electromagnets and the iron rails on the guideway increases as the gap between them decreases, the Transrapid Levitation system maintains stability by servo control of the current that energizes the magnets. Upwards movements of the vehicle are countered by decreasing the magnet current, while downwards movements from the rails are increasing the magnet current.

Rather than relying on the passive stability inherent in the superconducting maglev system, where any small displacement from the equilibrium suspension point is automatically countered by an induced magnetic force in the guideway, the

Transrapid system thus relies on active stabilization to maintain levitation of the maglev vehicles. The gap between the vehicle and the guideway is continuously monitored, and the current in the electromagnets continuously adjusted on a fast time scale of thousandths of a second, so as to maintain a constant value for the vehicle guideway gap. The magnitude of the gap is small, about 3/8ths of an inch. In comparison, superconducting maglev operates with a larger vehicle/guideway gap, typically on the order of 4 to 6 inches. The large gap allows the tolerances for construction of superconducting maglev guideways to be greater. Greater tolerances enable lower guideway cost and reduce sensitivity to earth settling, thermal expansion effects and earthquake movements.

Transrapid has demonstrated safe and reliable operation of its Maglev vehicles at speeds up to 280 mph on its 35 kilometer test track in Emsland, Germany, on which it has carried hundreds of thousands of passengers. Transrapid has been certified as ready for commercial service. China planed to build a system for the Shanghai Airport, which is now in operation.

5. QUESTIONS WITH ANSWERS ABOUT MAGLEV

5.1 Introduction

Through the earlier coverage of the highly complex field of the Maglev system in a rather simplified manner, it will have been seen that it requires cooperative efforts involving the resources of many disciplines. While in practice one may be involved in the development / research of one or two technical aspects of Maglev, it is important to have a perspective about the complexity of the overall picture. In the following, we attempt to provide such a perspective in a simple question and answer form.

5.2 Questions with their Answers about Maglev[79-80, 88-94, 100]

5.2.1 Q. Why there is need for Maglev?

A. Efficient, low cost transport is a critical and indispensable necessity for civilization. Without it, humans would still live at subsistence level, and in Hobbes' famous quote, our lives would be "poor, nasty, brutish, and short". One may argue about the exact order of evolution of different modes of transportation- did ships really precede wagons? - or their importance in society - for some countries, wagons are more important than autos, aircraft, or rockets - but all play an important role in the world economy. Looking at the list[79], one is struck by three general conclusions. First, as each new mode of transport is introduced, there is a quantum jump in transport capability - the new mode does things the older modes could not do. Moreover, where the new mode does directly compete with the old modes, it generally does so more efficiently and at lower cost. Railroads, for example, could move people and goods, faster, more efficiently and more cheaply

Major Modes of Transport

- Ships
- Wagons
- Railroads
- Pipelines
- Autos, Trucks, and Buses
- Aircraft
- Rockets

than wagons. In turn, autos, trucks and buses could serve many more points than railroads, which would go broke if they attempted to lay track to every origin and destination point. Second, with the possible exception of rockets, all of the transport modes have essentially matured. Further performance gains in speed, carrying capability and unit cost of transport, appear marginal at best. In fact, in some respects, performance is likely to worsen. Higher traffic loads are reducing the average speed on the highways, and increasing the delays at airports. As the cost of fuel increases, the unit costs of transport will also go up.

Third, with the exception of wagons, pipelines, and electrified railroads, all of the transport modes require fossil fuel - primarily, petroleum - to operate. The world currently consumes approximately 80 million barrels of oil per day, most of which is used for transport. At 30 dollars a barrel, the world spends almost a trillion dollars annually for oil. Petroleum resources are being rapidly depleted and will be largely gone in a few decades. As resources deplete, the cost per barrel will rapidly escalate. As a result, the above modes of transport will either have to electrify - difficult for autos, trucks, and buses, and impossible for aircraft - or have to depend on synthetic fuels. Such fuels will be even more expensive than present ones. Moreover, since they will primarily be derived from coal, oil shale, etc., they will continue to release large amounts of carbon dioxide into the environment, further increasing global warming.

Why there is need for maglev? Basically because it offers a way out from the inherent and unfavorable limitations of the existing transport modes. What are the benefits and advantages of maglev[80], compared to existing transport modes? Unique new markets enabled by maglev include the capability to transport water for hundreds of miles much more cheaply than pipelines, the capability to transport passengers at 2000 mph in low pressure tunnels, and the capability to launch to space at very low cost.

5.2.2 Q. What are the benefits and advantages of Maglev?

A. The following table brings about the significance of the benefits and advantages of Maglev :

Benefits and Advantages of Maglev
Inherent Advantages of Maglev • Much greater mobility • Freedom from delays due to traffic congestion and weather conditions
Environmental Advantages • Minimum land use and environmental impact • Ideally zero pollution – much less energy than autos, trucks and airplanes • No carbon dioxide emissions when powered by solar, wind, hydro and other forms of non-fossil power
Consumer Benefits • Major reductions in travel costs, for both passenger and freight • Much greater passenger comfort, through greater seating space, and absense of vibration and noise
New Markets and Opportunities • Long distance, low cost transport of water • Ultra high speed transport over continental distances • Ultra low cost launch of payloads into orbit

5.2.3 Q. How much will it cost to travel by Maglev compared to airplanes? Will it be faster or slower, more comfortable?

A. The average cost for air travel is about 13 cents per passenger mile. This includes labor, airplanes, fuel, and other costs, and corresponds to a ticket price of about $600 round trip, for a coast-to-coast flight. Some tickets cost less, some more, for a particular flight, depending on the discount offer, date of purchase, age, and so on.

The 13 cents per passenger mile does not include government subsidies for airports, highway access, FAA operations, etc.

M-2000 Maglev operational costs for vehicles, energy, and labor total about 4 cents per passenger mile, not including the amortization cost for the guideway. Projecting guideway amortization cost is difficult since it depends on ridership and whether the guideway carries freight as well as passengers. For a M-2000 guideway cost of 10 million dollars per 2-way mile, that carries only passengers, amortization cost is about 10 cents per passenger mile, assuming a 30-year payback period and 10,000 passengers daily. If the guideway carries 1000 trailers daily and allocates 3 cents per ton mile (30 tons per trailer} of revenue to guideway amortization, the passenger share for guideway amortization is zero cents per passenger mile. Total cost for passengers is then only 4 cents per passenger mile, about 1/3 of that for air travel. If M-2000 guideways carry both passengers and truck type freight, Maglev will be much cheaper than air travel.

Although jet aircraft speed is greater than Maglev (500 mph compared to 300 mph) the actual trip time will be much less for Maglev. First, access to Maglev stations will be much easier and faster than airports. With the M-2000 National Maglev Network, over 70% of the population will live within 15 miles of a Maglev station, which they could reach in a few minutes. Second, the departure frequency of Maglev vehicles will be much greater than for aircraft. Most airports have only a few flights daily to a given destination: Maglev stations will typically have dozens. Third, Maglev schedules will not be upset by bad weather or congestion, which is often the case for air travel.

Finally, because Maglev vehicles are much cheaper than airliners -a few million dollars per vehicle, compared to a 100 million dollars or more for an airliner - and because their operating cost is very low, Maglev travel will be much more comfortable than air travel. There is no need to pack riders in like sardines to save money -passengers will travel in first class style, for lower cost than economy air. Moreover, the vibration and noise experienced on airliners are completely absent on Maglev vehicles.

5.2.4 Q. Why is Maglev better than the High-Speed Trains already operating in Europe and Japan?

A. Maglev is better than high-speed trains for many reasons. First, rather than the point-to-point service between city centers characteristic of high speed rail, Maglev will have many more stations, distributed so that people have easy and fast access to the Maglev Network. Second, individual Maglev vehicles will hold 100 people at most, compared to the 500 to 1000 people on a high-speed train. This enables more frequent and convenient service. Third, Maglev vehicles travel at 300 mph, compared to 180 mph for high-speed trains. The faster Maglev vehicles, plus their ability to accelerate and decelerate much more quickly, cut the travel time for Maglev by at least a factor of 2, as compared to high speed rail. Fourth, the Maglev noise is much less than steel wheels on rail. Finally, Maglev vehicles travel on elevated guideways, something that the much heavier trains cannot do. Elevated Maglev guideways enhance safety and reduce environmental impact, compared to an on-grade rail track.

5.2.5 Q. How will Maglev change my life, other than making it easier to take trips?

A. Maglev will dramatically change the way people live in the 21st Century, with effects far beyond those associated with personal trips. First, and very important, with Maglev people will live much farther from their work place and from city centers, while still being able to travel to them in a short time. Spreading population over a much larger area than is possible with present transport systems will greatly reduce the cost of owning a home, and allow people to enjoy nature much more.

Second, sending trailer trucks by Maglev instead of on highways will cut the costs of goods, increase highway safety, reduce congestion and delays, and make the highways last much longer.

Third, Maglev will greatly reduce pollution, extend oil resources and help keep oil and gas prices reasonable, and lessen the rate at which carbon dioxide is released into the atmosphere. This will help slow global warming.

Fourth, Maglev because of its potential for greatly reducing the cost of launching payloads into orbit will open up space to much greater usage, colonization, and eventually tourism.

5.2.6 Q. Why are superconducting magnets used in the Japanese and M-2000 Maglev systems? What are the advantages and disadvantages of superconducting magnets?

A. Superconducting magnets are used in the M-2000 and Japanese Maglev Systems for the following reasons:

- Superconducting magnets enable Maglev vehicles to operate with much greater clearances above the guideway, than are possible with room temperature magnets. With superconducting magnets, the gap between the Maglev vehicle and the guideway can be 6 inches. With room temperature electromagnets or permanent magnets, the gap is only about 3/8 of an inch. Large gaps improve safety, allow greater construction tolerances, decrease construction costs, and reduce sensitivity to ground settling and earthquakes.
- Superconducting magnets enable the levitated vehicle to be inherently and passively strongly stable against external forces (winds, grades, curves, etc.) that act to displace the vehicle from its normal suspension point. Attractive force suspensions based on room temperature electromagnets are inherently unstable, and require constant, fast response servo control of the magnet current to operate safely.
- Superconducting magnets let Maglev vehicles levitate much heavier loads than are possible with room temperature electromagnets or permanent

magnets. Heavier load capacity lets Maglev vehicles carry freight, water, mining ores, etc., to generate large revenues.

- Superconducting magnets have much lower power requirements than conventional room temperature electromagnets.

The only disadvantage of superconducting magnets is their need for refrigeration. However, the power for the refrigerator is small compared to the power to overcome air drag on the vehicle. Accordingly, operating cost for superconductors is a minor perturbation.

The superconducting magnets on Maglev vehicles are not complicated to construct or operate. Thousands of superconducting magnets now operate routinely and reliably around the world in MRI devices, high-energy accelerators, and other applications.

5.2.7 Q. What is a superconducting magnet? How is it different from ordinary magnets?

A. The main difference between superconducting magnets and conventional room temperature electromagnets, is that they use low temperature, zero electrical resistance conductor wire in the magnet winding, instead of room temperature, non-zero electrical resistance conductor. Conventional electromagnets use aluminum or copper conductor, while superconductor magnets use niobium-titanium-copper wire (or other superconductor, depending on application). Also, conventional electromagnets often use iron cores to reduce the current and I^2R losses in the conductor winding.

Because superconductors have no electrical resistance, very high currents and current densities are practical, resulting in much more powerful electromagnets than are possible with room temperature conductors. While room temperature permanent magnets have no current windings or I^2R losses, their inherent physical characteristics limit their magnetic field capabilities to much less than those of superconducting magnets.

Superconducting magnets require good thermal insulation to keep the superconductors cold. They also have to be cooled with helium (for low temperature superconductors) or nitrogen (for high temperature super conductors) compared to conventional electromagnets which are cooled by ordinary water.

5.2.8 Q. Are superconducting magnets really dependable? Will it be safe to travel by Maglev?

A. Superconducting magnets are highly reliable. High-energy accelerators routinely operate with many hundreds of superconducting magnets positioned along the path followed by particles that travel in precise orbits along miles of evacuated tubes. If only one of these many hundred magnets failed, it would shut down the accelerator for a long period while the magnet was repaired or replaced. Such a situation could not be tolerated, and in fact, does not occur in practice. In the proposed superconducting super collider (SSC), for example, over 10,000 superconducting magnets would have been positioned along the 76-kilometer circumference of the SSC. Failure of one of these magnets would have shut down the SSC.

The M-2000 Maglev vehicles are designed with multiple (typically 16) superconducting magnets that operate separately and independently of each other. The M-2000 vehicle will remain levitated and operate safely even if several of its magnets were to fail. Because the failure rate of superconducting magnets is very low, the probability of two magnets failing in a period of few minutes, the time needed to reach a stopping point, would be less than once in a million years of operation.

Such a failure rate is much smaller than the engine failure rate in jet aircraft. Furthermore, the Maglev vehicle would continue to operate, while the jet aircraft would not. In fact, it would take the simultaneous failure of at least 6 independent magnets to compromise levitation capability -a probability that is infinitesimally small compared to other modes of transport.

5.2.9 Q. What happens if the electric power is cut off to a Maglev guideway? Will the vehicles on it crash?

A. The M-2000 vehicles are automatically and passively stably levitated as long as they move along the guideway. The electric power fed to the guideway magnetically propels the M-2000 vehicles and maintains their speed. If the guideway power were cut off, the vehicles would coast for several miles, gradually slowing down due to air drag. When they reach 30 mph, they settle down on auxiliary wheels and brake to a stop on the guideway. When power is restored to the guideway propulsion windings, the vehicles can magnetically accelerate back up to their cruising speed.

Because the vehicles are automatically levitated and stabilized for speeds greater than 30 mph, there is no chance of a crash if guideway power is cut off.

5.2.10 Q. Are there any health or environmental hazards from the magnetic fields of a Maglev vehicle?

A. There are no health and environmental hazards from the magnetic fields around the M-2000 Maglev vehicle. The magnetic fringe fields from the quadrupole magnets on the M-2000 vehicles drop off much faster with distance than do the fringe fields from dipole magnets. This rapid decrease in fringe fields allows the magnetic fields in the passenger compartment to be at Earth ambient level, ~ 0.5 Gauss. All humans live constantly in Earth's magnetic field and are adapted to it. They will experience no difference in field strength when they ride in a M-2000 Maglev vehicle.

In fact, people presently experience stronger magnetic fields than the Earth ambient value when they ride subways and electrified trains, when they operate electrically powered equipment in the home or when they walk down city streets. The magnetic fields in M-2000 vehicles will be lower than in the above examples.

5.2.11 Q. Why don't we already have Maglev systems? If they are as good as you say, why aren't they being built?

A. There is a tremendous investment, both in money and human experience, in our present modes of auto, truck, air, and rail transport. The US spends almost a trillion dollars annually on these transport systems. Until recently, they have functioned adequately.

Moving into a new transport mode like Maglev is difficult and takes time, because of the large capital investments required, and the need for people to acquire new job skills and change their ridership habits. Such a shift requires demonstration Maglev systems to convince the public that Maglev is real. Such demonstrations are now at hand. Moreover, the increased congestion, delays, and costs of transport on the nation's highways and airways will help speed the transition to Maglev.

5.2.12 Q. You state that Maglev vehicles can deliver trailers and freight containers over long distances at high speed and low cost. What about personal autos?

A. It appears practical to transport autos by Maglev over long distances. Such capability would be attractive for vacationers, since it would be much faster and more comfortable than driving hundreds of miles. To transport an auto from New York to Chicago by Maglev, a distance of 800 miles, would cost about 100 dollars.

5.2.13 Q. What are the advanced performance capabilities of the American M-2000 superconducting Maglev system?

A. The following table gives the advanced performance capabilities of the American M-2000 superconducting Maglev system.

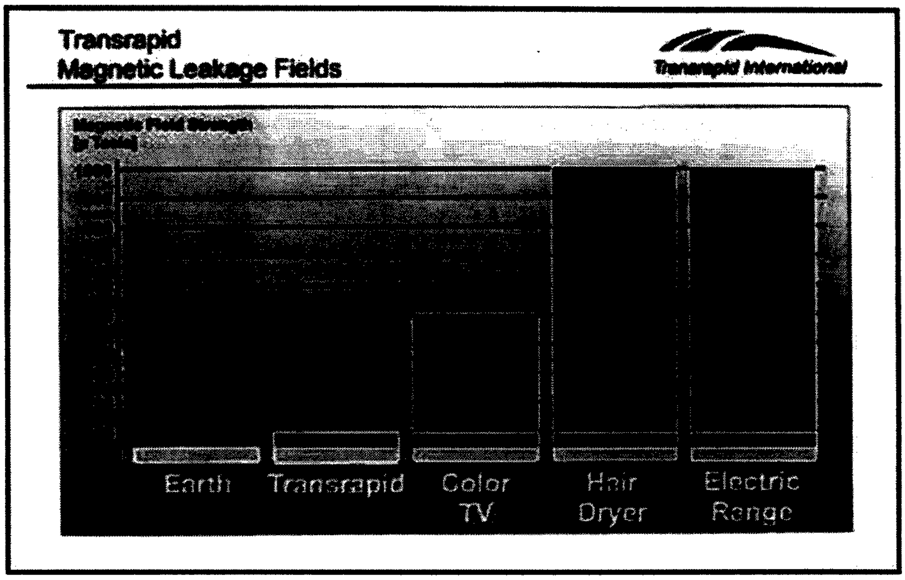
Advanced Performance Capabilities of the M-2000 Maglev system
• Guideway carries both passengers and freight vehicles
• Vehicles can travel on either narrow beam or planar guideways and transition from one to the other
• Vehicles can electronically switch at 300 miles per hour to off-line stations
• Low guideway capital cost (~10 million dollars per two-way mile)
• Magnetic fields in the passenger compartment are at Earth ambient level

5.2.14 Q. What are the differences between High-Speed Maglev and the low speed system?

A. High-Speed Maglev is a fully operational mode of transportation that can function both as an intercity system as well as a local transit operation. It was originally developed in Germany using conventional electromagnets and has gone through 25 years of testing and operation. The low speed system, which will have the characteristics primarily of a downtown people - mover, is still in the planning stages and has yet to be fully developed.

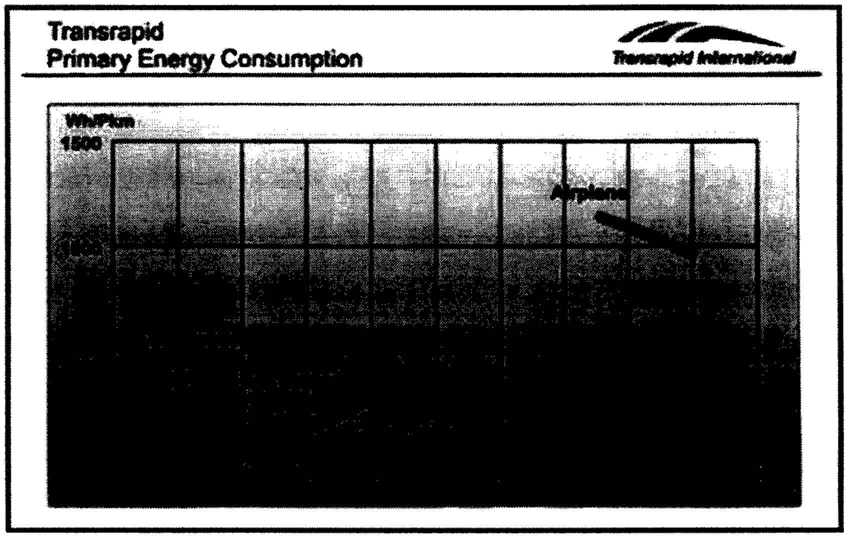
5.2.15 Q. What about the electromagnetic radiation of maglev as compared to other modes of transport?

A. The levitated air gap for the Transrapid International high-speed Maglev is very small - about 3/8 of an inch. This small gap keeps the electromagnetic field very well confined and greatly reduces the extent of the electromagnetic fields. The measured field strength of the Transrapid's stray magnetic fields is extremely low. It is comparable with the residual strength of the earth's magnetic field and therefore several hundred times lower than that of many household appliances. Passengers are not exposed to magnetic fields in excess of the earth's magnetic field and therefore there is no fear of interference with pacemakers or other life supporting apparatus. The following graph provides the electromagnetic radiation of German maglev Transrapid as compared to other modes of transport.



5.2.16 Q. What about the energy usage of maglev as compared to other modes of transport?

A. The following graph provides the energy usage of German maglev Transrapid as compared to other modes of transport.



6. BIBLIOGRAPHY

1. H. Kamerlingh Onnes, *Leiden Comm.* **120b, 122b, 124c,** 1911.
2. H. Kamerlingh Onnes, Further experiments with liquid helium. H. On the electrical resistance of pure metals etc. (continued). VIII. The sudden disappearance of the ordinary resistance of tin, and the super-conductive state of lead, *Comm. Phys. Lab. Leiden,* **133d:** 51, 1913.
3. W. Meissner and H. Franz, Messungen mit Hilfe von flüssigen Helium. VIII. Supraleitfähigkeit von Niobium, *Physikalisch-Technische Reichsanstalt Mitteleilung,* 558-559, 1930.
4. W. Meissner and R. Oschenfeld, Ein neuer Effect bei Eintritt der Supraleitfähigkeit, *Naturwiss.,* **21:** 787-788, 1933.
5. F. London and H. London, The electromagnetic equations of the supraconductor, *Proc. Roy. Soc. London Ser. A,* 71-88, 1935.
6. V. L. Ginzburg and L. D. Landau, On the theory of superconductivity, *Zh. Eksp. Teor. Fiz.* **20:** 1064-1082, 1950.
7. A. B. Pippard, An experimental and theoretical study of the relation between magnetic field and current in a superconductor, *Proc. Roy. Soc. London,* **A216,** 547, 1953.
8. L. N. Cooper, Bound electron pairs in a degenerate Fermi gas, *Phy. Rev.,* **104:** 1189-1190, 1956.
9. J. Bardeen, L. N. Cooper, and J. R. Schreiffer, Theory of superconductivity, *Phy. Rev.,* **108:** 1175-1204, 1957.
10. L. P. Gorkov, Theory of superconducting alloys in a strong magnetic field near the critical temperature, *Sov. Phys. JETP,* **10:** 998-1004, 1960.
11. A. A. Abrikosov, *Zh. Eksperim. I Teor. Fiz.,* **32:** 1442, 1957.
12. L. P. Gorkov, *Zh. Eksperim. I Teor. Fiz.,* **36:** 1918, 1959.
13. B. D. Josephson, *Phy. Letters,* **1:** 251, 1962.
14. G. Bednorz and K. A. Müller, Possible high T_c superconductivity in the Ba-La-Cu system, *Z. Phys. B,* **64:** 189-197, 1986.
15. M. K. Wu et al., Superconductivity at 93 K in a new mixed-phase Y-Ba-Cu-O compound system at ambient pressure, *Phys. Rev. Lett.,* **58:** 908-910, 1987.
16. Z. Z. Sheng and A. M. Hermann, 90 K Tl-Ba-Cu-O and 120 K Tl-Ca-Ba-Cu-O bulk superconductors, *Proc. 1988 World Congress on Superconductivity,* Singapore: World Scientific, pp. 365-376, 1988.
17. M. Cantoni et al., Characterisation of superconducting Hg-Ba-Ca-Cu-oxides. Structural and physical aspects, *Physica C,* **215:** (1-2): 11-18, 1993.
18. P. Dai et al., Synthesis and neutron powder diffraction study of the superconductor $HgBa_2Ca_2Cu_3O_{8+\delta}$ by Tl substitution, *Physica C,* **243:** (3-4): 201-206, 1995.
19. E. Krestel (ed.), *Imaging Systems for Medical Diagnostics,* Berlin and Munich: Siemens, 1990.
20. J. D. Bronzino (ed.), *The Biomedical Engineering Handbook,* Boca Raton: CRC Press, IEEE Press, 1995.

21. R. Fenici and G. Melillo, Magnetocardiography: Ventricular arrhythmias, *Eur. Heart J.*, **14** (Suppl. E): 53-60, 1993.
22. J. D. Lewine W. W. Orrison, Magnetoencephalography, in W. G. Bradley and G. M. Bydder (eds.), *Advanced MR Imaging Techniques*, London: Martin Dunitz, 1997, pp. 333-354.
23. J. Knuutila et al., Design considerations for multichannel SQUID magnetometers, in H. D. Hahlbohm and H. Lubbig (eds.), *SQUID'85: Superconducting Quantum Interference Devices and their Applications*, Berlin: de Gruyter, 1985, pp. 939-944.
24. J. P. Mäkelä, Functional differences between auditory cortices of the two hemispheres revealed by whole-head neuromagnetic recordings, *Hum. Brain Mapp.*, **1:** 48-56, 1993.
25. R. Fenici et al., Clinical validation of three-dimensional cardiac magnetic source imaging accuracy with simultaneous magnetocardiographic mapping, monophasic action potential recordings, and amagnetic cardiac pacing, *11th Int. Conf. Biomagnetism, Biomag98*, Abstracts, Sendai, 1998, p. 119.
26. A. Zhukovsky et al., 750 MHz NMR magnet development, *IEEE Trans. Magn.*, **MAG-28:** 644-647, 1992.
27. D. G. Hawksworth, Superconducting magnets systems for MRI, *Int. Symp. New Develop. in Appl. Superconductivity*, Singapore: World Scientific, 1989, pp. 731-744.
28. B. D. Josephson, Possible new effect in superconductive tunneling, *Phys. Lett.*, **1:** 251-253, 1962.
29. R. P. Giffard, R. A. Webb, and J. C. Wheatley, Principles and methods of low-frequency electric and magnetic measurements using an rf-biased point-contact superconducting device, *J. Low Temp. Phys.*, **6:** 533-610, 1972.
30. R. L. Fagaly, Neuromagnetic instrumentation, in S. Sato (ed.), *Advances in Neurology, Vol. 54: Magnetoencephalography*, New York: Raven Press, 1990.
31. C. Heiden, Pulse tube refrigerators: A cooling option, in H. Weinstock (ed.), *SQUID Sensors: Fundamentals, Fabrications and Applications*, Dordecht: Kluwer, 1997.
32. M. J. Wengler, Submillimeter-wave detection with superconducting tunnel diodes, *Proc. IEEE*, **80:** 1810-1826, 1992.
33. A. Skalare et al., A heterodyne receiver at 533 GHz using a diffusion cooled superconducting hot electron mixer, *IEEE Trans. Appl. Supercond.*, **5:** 2236-2240, 1995.
34. M. Morpurgo, Construction of a superconducting test coil cooled by helium forced circulation, *Proc. 1968 Summer Study Superconducting Devices Accelerators*, BNL 50155 (C-55), 953, 1968.
35. M. A. Green, Calculating the Jc, B, T surface for niobium titanium using the reduced state model, *IEEE Trans. Magn.*, **MAG-25:** 2119, 1989.
36. R. A. Wood, High performance infrared thermal imaging with monolithic silicon focal planes operating at room temperature, *Int. Electron Devices Meet.*, Washington, DC, 1993, pp. 175-177.

37. A. Jahanzeb et al., Studies and implications of the Hall-effect in superconducting and semiconducting $YBa_2Cu_3O_{7-\infty}$ thin films, *J. Appl. Phys.*, **78:** 6658, 1995.

38. C. M. Travers et al., Fabrication of semiconducting YBaCuO surface micromachined bolometer arrays, *IEEE/ASME J. Microelectromech. Syst.*, **6:** 271-276, 1997.

39. D. Mihailovic, I. Poberaj, and A. Mertelj, Characterization of the pyroelectric effect in $YBa_2Cu_3O_{7-\delta}$, *Phys. Rev. B*, **48:** 16,634-16,640, 1993.

40. O. Vendik, I. Mironenko, and L. Ter-Martirosyan, Superconductors Spur Applications of Ferroelectric Films, *Microwaves and RF*, **33** (7): 67-70, 1994.

41. A. V. Tollestrup, Superconducting magnets, *AIP Conf. Proc.*, **87:** 1982, pp. 699-804.

42. R. Meinke, Superconducting magnet system for HERA, *IEEE Trans. Magn.*, **27:** 1728-1734, 1991.

43. V. I. Balbekov and G. G. Gurov, IHEP accelerating and storage complex: Status and possibility of B-factory, *Nucl. Instrum. Meth. Phys. Res.*, A **333:** 189-195, 1993.

44. R. I. Schermer, Status of superconducting magnets for the superconducting super collider, *IEEE Trans. Magn.*, **30:** 1587-1594, 1994.

45. A. Greene et al., The magnet system of the relativistic heavy ion collider (RHIC), *IEEE Trans. Magn.*, **32:** 2041-2046, 1996.

46. R. Perin, Status of LHC programme and magnet development, *IEEE Trans. Appl. Supercond.*, **5:** 189-195, 1995.

47. J. Cornell, *Cyclotrons and Their Applications*, Singapore: World Scientific, 1996.

48. E. Weihreter, *Compact Synchrotron Light Sources*, Singapore: World Scientific, 1996.

49. J. E. Lenz, A review of magnetic sensors, *Proc. IEE*, **78** (6): 973-989, 1990.

50. R. Brinkmann, in *Proceedings of the 1995 Particle Accelerator Conference*, Cat. No. 95CH35843, 1995, p. 674.

51. $\mu^+\mu^-$ Collider, *A Feasibility Study*, BNL-52503, 1996.

52. J. W. Ekin, A. J. Panson, and B. A. Blankenship, Method for making low-resistivity contacts to high T_c superconductors, *Appl. Phys. Lett.*, **52:** 331-333, 1988.

53. I. Vendik et al., The Superconducting microwave devices based on S-N transition in HTS films, *27th Eur. Microw. Conf. Proc.*, 1997, pp. 909-914.

54. S. H. Talisa et al., High-temperature superconducting space-qualified multiplexers and delay lines, *IEEE Trans. Microw. Theory Tech.*, **44:** 1229-1239, 1996.

55. J. Iannicelli, and S. Malghan, (ed.), Paramagnetic separation in ultrafine industrial minerals and coal, *Ultrafine Grinding and Separation of Industrial Minerals*, New York: American Institute of Mining, Metallurgical and Petroleum Engineers Inc., 1983, p. 105.

56. Eriez Magnetics, *Products Catalog*, Erie, PA, 1997.

57. J. Iannicelli et al., *IEEE Trans. Appl. Supercond.*, **7** (2): 1061-1064, 1997.

58. Carpco, *Products Catalog,* Jacksonville, FL, 1998.

59. S. Dale, S. Wolf, and T. Schnieder, *Energy Applications of High-Temperature Superconductivity,* 2, 1976.

60. R. Mitchell and D. Allen, *Industrial Applications of Magnetic Separation,* IEEE Catalog No. 78CH1447-2, 1979, p.142.

61. L. A. Worl, et al., Magnetic separation for nuclear material and surveillance, *Emerging Technologies in Hazardous Waste Management,* Proc. 216th American Chemical Society Conference, Boston MA, 1998.

62. A. D. Inglis and I. Minowa, Fabrication of precision quantized Hall devices, *IEEE Trans. Instrum. Meas.*, **46:** 205-207, 1997.

63. W. V. Hassenzahl, Applications of superconductivity to electric power systems, *IEEE Power Eng. Rev.*, **20** (5): 4-7, 2000. W. V. Hassenzahl, More applications of superconductivity to electric power systems, *IEEE Power Eng. Rev.*, **20** (6): 4-6, 2000.

64. N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics—Converters, Applications and Design,* New York: Wiley,1995.

65. Draft Standard, Electric Power System Compatibility with Electronic Process Equipment, IEEE P1346 Working Group.

66. M. N. Wilson, *Superconducting Magnets,* Oxford, UK: Clarendon Press, 1983, pp. 41-47.

67. H. Kado and M. Ichikawa, Performance of a high-T_c superconducting fault current limiter. *IEEE Trans. Appl. Supercond.,* **7:** 993-996, 1997.

68. T. A. Kozman et al., Magnets for the mirror fusion test facility: Testing of the first Yin-Yang and the design and development of the other magnets, *IEEE Trans. Magn.,* **19:** 859, 1983.

69. D. P. Ivanov et al., Test results of "tokamak-7" superconducting magnet system (SMS) sections, *IEEE Trans. Magn.,* **15:** 550, 1979.

70. J. Sapper, The superconducting magnet system for the Wendelstein 7-X stellarator, *Proc. Annu. Meeting Amer. Nuclear Soc.* (ANS), Reno, NV, 1996.

71. L. R. Grisham et al., The scaling of confinement with major radius in TFTR, *Phys. Rev. Lett.*, **67:** 66-69, 1991.

72. K. Sakamoto et al., Development of high power 170 GHz 1 MW gyrotron for ITER, *Proc. Twenty Second Int. Conf. Infrared Millimeter Waves,* Wintergreen, VA, July 1997.

73. M. Yamamoto, A Study on a Coreless Superconducting Transformer, *IEEE Trans. Appl. Supercond.,* **3:** 889, 1993.

74. B. W. McConnell, S. Mehta, and M. S. Walker, HTS transformers, *IEEE Power Eng. Rev.*, **20** (6): 7-11, 2000.

75. A. A. Kordyuk, Magnetic levitation for hard superconductors, *J. Appl. Phys.* **83** (1): 610-612, 1998.

76. A. A. Kordyuk and V. V. Nemoshkalenko, High-speed magnetic rotor with HTS bearings for precision energy losses investigations, *IEEE Trans. Appl. Supercond.* **7:** 928-931, 1997.

77. W. Göpel, J. Hesse, and J. N. Zemel (eds.), *Sensors, A Comprehensive Survey,* Vol. 4, *Thermal Sensors,* T. Ricolfi, J. Scholz (eds.), Weinheim: VCH, 1990.

78. D. P. De Witt and G. D. Nutter (eds.), *Theory and Practice of Radiation Thermometry,* New York: Wiley, 1988.

79. Chip Moore (ed.), *National Transportation Statistics 2002,* Washington, DC: Bureau of Transportation Statistics (BTS), U. S. Department of Transportation, December 2002.

80. The Maglev Technology Advisory Committee Reporting to the United States Senate Committee on Environment and Public Works, *Benefits of Magnetically Levitated High Speed Transportation for the United States,* Volume **1,** Executive Report, New York: Grumman Corporation, Bethpage, June 1989.

81. U.S. Department of Transportation/Federal Railroad Administration Report to Congress, Assessment of the Potential for Magnetic Levitation Transportation Systems in the United States, Moving America, New Directions, New Opportunities, June 1990.

82. H. T. Coffey, U. S. Maglev: Status and Opportunity, *IEEE Trans. Appl. Supercond.,* **3:** 863-868, 1993.

83. J. R. Powell, and G. T. Danby, Magnetic suspension for levitated tracked vehicles, *Cryogenics,* **11:** 192-204,1971.

84. Okumura Fuminao, Development of Superconducting Maglev in Japan, *Journal of Japanese Trade and Industry,* Tokyo: Mar/Apr,2001.

85. Thor Windbergs, Germany's Transrapid: Gliding into the Future of Mass Transportation, *Colorado Engineer Magazine, Fall/Winter, 1997,* University of Colorado, 1997.

86. Curtis F Berthelot, History of Transportation, *Introduction to Transportation Engineering,* 15, Transportation Research Centre, University of Saskatchewan, Saskatoon: Jan, 2003.

87. T. D. Rossing and J. R. Hull, Magnetic levitation, *Phys. Teacher,* **29** (9): 552-562, 1991.

88. E. R. Laithwaite (ed.), *Transport without Wheels,* London: Elek Science, 1977.

89. F. C. Moon, *Superconducting Levitation,* New York: Wiley,1994.

90. R. G. Rhodes and B. E. Mulhall, *Magnetic Levitation for Rail Transport,* Oxford: Clarendon Press, 1981.

91. T. D. Rossing and J. R. Hull, Magnetic Levitation comes of age, *Quantum* **5** (4): 22-27 March/April 1995.

92. A. A. Kordyuk, Magnetic levitation for hard superconductors, *J. Appl. Phys.* **83** (1): 610-612, 1998.

93. H. Bleuler, A survey of magnetic levitation and magnetic bearing types, *JSME Int. J. Ser. III.,* **35:** 335-342, 1992.

94. B. V. Jayawant, Electromagnetic suspension and levitation, *Rep. Prog. Phys.,* **144:** (1981). Also Electromagnetic suspension and levitation techniques, *Proc. Roy. Soc. London A,* **416:** 245-320, 1988.

95. J. C. Maxwell, *A Treatise on Electricity and Magnetism,* Vol. 2, Oxford: Clarendon Press, 1891. Reprinted by Dover, New York 1954.

96. J. C. Maxwell, On the induction of electric currents in an infinite plane sheet of uniform conductivity, *Proc. Roy. Soc. London A,* **20:** 160-168, 1872.

97. W. M. Saslow, How a superconductor supports a magnet, how magnetically 'soft' iron attracts a magnet, and eddy currents for the uninitiated, *Am. J. Phys.,* **59:** 16-25, 1991.

98. W. M. Saslow, On Maxwell's theory of eddy currents in thin conducting sheets and applications to electromagnetic shielding and MAGLEV, *Am. J. Phys.,* **60:** 693-711, 1992.

99. J. R. Reitz, Forces on moving magnets due to eddy currents, *J. Appl. Phys.,* **41:** 2067-2071, 1970.

100. Z. J. Yang, Lifting forces acting on magnets placed above a superconducting plane, *J. Supercond.,* **5** (3): 259-271, 1992.

101. J. R. Hull, guest editor, *Applied Superconductivity,* **2** (7/8): 1994. Contains several state-of-the-art papers on superconducting levitation.

102. R. R. Heikes and R. W. Ure, Jr., *Thermoelectricity: Science and Engineering,* New York: Interscience Publishers, 1961.

103. H. J. Goldsmid, *Thermoelectric Refrigeration,* New York: Plenum, 1964.

104. M. M. Leivo, J. P. Pekola, and D. Averin, Efficient Peltier refrigeration by a pair of normal metal/insulator/superconductor junctions, *Appl. Phys. Lett.,* **68:** 1996, 1996.

105. D. Driscoll, V. Dombrovski, and B. Zhang, Development status of superconducting motors, IEEE *Power Eng. Rev.,* **20** (5): 12-15, 2000.