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Superconductors: Fact or Fiction?

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HISTORY

Superconductivity - a buzzword? No - it is a real life example of perpetual motion at the atomic level. A subject of great significance to our technological society and especially to us in the electrical industry.

Heike Kamerlingh Onnes, a Dutch physicist, first discovered superconductivity in 1911 while studying the effects of extremely cold temperatures on the properties of metals. He discovered that mercury lost all resistance to the flow of electricity when cooled to 4 deg. Kelvin. This was accomplished by immersing it in liquid Helium. Onnes performed the closed loop experiment described above and found that the current he had initially impressed on a coil was exactly the same 12 months later. Onnes was awarded the Nobel prize in physics in 1913 for his discovery and research into the fundamentals of superconductivity.

For nearly 50 years superconductivity defied explanation and was one of the outstanding puzzles of physics. Our present understanding gradually evolved through a long series of experimental and theoretical undertakings by many people working in laboratories throughout the world. It was not until 1957 that the theoretical basis of superconductivity was established by Bardeen, Cooper and Schrieffer at the University of Illinois. It is known as the BCS theory from the initials of its founders and was worthy of a Nobel prize.

Major stimulus to research was given as potential applications of the phenomena became apparent. Temperature became the primary limiting factor for practical applications. The initial work by Onnes in 1911 was performed at a temperature of 4 deg. K. By 1933 superconductivity was achieved at 10 deg. K., still in a liquid helium environment. It was not until 1969 when the temperature was doubled to 20 deg. K. that it was possible to use a new coolant, liquid Hydrogen. In 1986 two IBM researchers in Zurich, using complex ceramic materials were successful at a temperature of 30 deg. K. The importance of their work was the development of new materials which offered hope for the achievement of superconductivity at higher temperatures.

In February of 1987 a major breakthrough occurred when Paul Chu and his research team at the University of Houston reported developing a superconductor composed of Barium, Yttrium and copper oxide in a crystalline form with a critical temperature of 98 deg. K. This achievement was preceded by many months of tedious checking of other combinations of elements. The discovery was of special importance, in that the coolant needed to achieve superconductivity, became liquid nitrogen. Liquid nitrogen costs less than 50 cents a liter and can be handled with great ease while liquid helium costs several dollars a liter and requires extensive facilities to contain and control the low temperature environment.

A fascinating description of the process and events leading to the discovery and the announcement of Dr. Chu's team's achievement is in a short book called "THE BREAKTHROUGH, The race for the Superconductor," by Robert M. Hazen, and printed by Summit Books.

Researchers throughout the world are seeking materials with higher temperatures. Validated results have not been achieved at this time. It is conceivable that we may see superconductivity achieved at room temperature. The ability of the human mind to overcome obstacles is almost limitless.

What is Superconductivity?

Let us describe what we mean when we talk about superconductivity. It is a condition in which a conductor has zero resistance to the flow of electricity as well as two further special properties, the Meissner effect, and the Josephson effect. The Meissner effect describes the lack of penetration of magnetic fields into a superconductor. The Josephson effect deals with use of the interface between the elements of a superconductor as a signal switching device similar to a semiconductor but approximately 100 times faster. The Meissner and Josephson effects will be described in greater detail later in this report.

To further describe the effect of zero resistance let us visualize a coil on which has been impressed a flow of current. Ordinarily the current would stop flowing in a brief period of time due to the internal resistance of the conductor, however, when the coil is superconductive the current will flow indefinitely.

The Science of Superconductivity

There are a number of factors involved in superconductivity that are worth our consideration.

1) Temperature
2) Resistance
3) Critical current
4) Magnetic field
5) Crystal Lattice Structure
6) Stability
7) Josephson effect

1) TEMPERATURE

Of the six performance criteria the requirement for cold temperatures is the most frequently mentioned.

What do we mean when we talk about extremely low temperatures? Minus 30 degrees, minus 100 degrees Fahrenheit - no - we are talking about absolute zero expressed as 0 deg. (K)elvin. Absolute zero is defined as the point where all atomic vibrations have stopped, or stated another way, matter is at its lowest state of energy. In the 1860's Lord Kelvin of Britain proposed an absolute thermodynamic scale of temperatures where zero degrees represented the temperatures for the condition described above. In order to provide a frame of reference, look at the comparative temperature chart.

	Degrees		
	Fahrenhei	Celsius	Kelvin
Absolute Zero	-459.4	-273	0
Liquid Helium forms	-451.84	-268.8	4.2
Liquid Nitrogen Forms	-320.8	-196	77
Water Freezes	32	0	273
Water Boils	212	100	373

Recent advances have brought the temperatures from 23 degrees K. to 294 degrees K. (almost room temperature). Unfortunately superconductors that work at room temperature only exist in controlled experimental environments and lack the reliable and reproducible qualities of the 98 degree K. superconductor.

2) RESISTANCE

A superconductor must exhibit zero resistance to direct currents and low frequency alternating currents until the critical current is reached. This is in direct conflict with a superconductor's resistivity to optical frequencies.

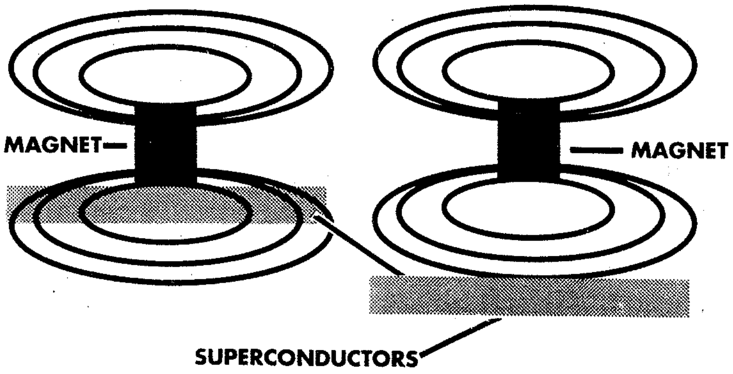
Not only is resistance current sensitive, but it is also variable over a fixed temperature range. An increase in temperature of 100 degrees K. from 98 degrees K. to 198 degrees K. with Yttrium copper oxides, will remove the complete resistivity of the superconductor.

3) CRITICAL CURRENT

Even under optimal operating temperatures, a superconductor loses its total resistivity at a specific current level called the critical current. IBM Research Labs have designed a superconducting thin film that exhibits a critical current of 100,000 A/sq. cm. Superconductors with high critical currents are necessary for turning lab experiments into production microelectronics.

4) MAGNETIC FIELD

In addition to displaying a complete absence of current resistance, superconductors also generate a magnetic field. This magnetic field generation is called the Meissner effect.

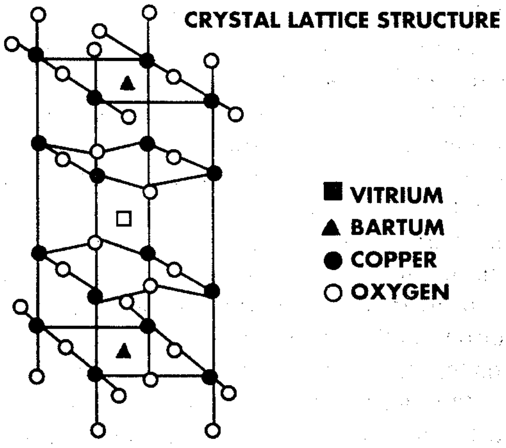


If a superconductor is cooled below its critical temperature while in a magnetic field, the magnetic field surrounds it but does not penetrate or affect the superconductor.

5) CRYSTAL LATTICE STRUCTURE

Both the lattice symmetry and the lattice spacing remain constant throughout a superconductor's transformation from its normal state into its superconducting state.

When atoms bond together to form a solid, they do so in a repetitive three dimensional grid pattern. This pattern is known as a lattice structure.



When current flows through a conductor, the electrons have to weave their way through the lattice. When an electron strays too close to an atom and is diverted from the flow, it transfers some of its energy to the lattice and this causes resistance in the conductor.

6) STABILITY

Superconductors must exhibit stability when reacting to other compounds. Even the reaction of a superconductor to water and air is an unpredictable factor in its function.

7) THE JOSEPHSON EFFECT

The Josephson effect is based on a phenomenon called tunneling. It occurs when a thin oxide barrier is sandwiched between two superconductors. As the superconductors are exposed to certain magnetic fields and radiation, the current flow can change because some electrons jump through the oxide barrier (tunneling).

A Josephson junction is a superconductivity switch that operates at frequencies 100 times faster than a transistor.

Another application is the detection of minute magnetic fields. These devices are known as SQUIDS (Superconductivity Quantum Interference Devices).

What materials make good Superconductors?

There are generally two classes of elements - Metals and non-metals. An attempt at separating these two groups is based on the ability of elemental oxides to form either bases or acids. In this clarification scheme elements like sodium are considered metals, whereas elements like carbon are labeled non-metals. Other characteristics used in separation of metals and non-metals include electrical conductivity, luster and opaqueness.

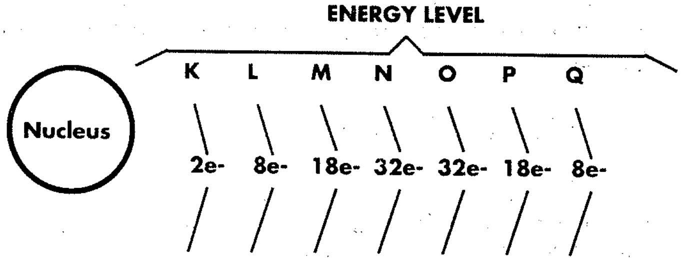
While the above qualities are suitable for the general clarification of metals and non-metals, they fail to adequately define the phenomenon of Superconductivity in metals. In order to understand the presence of this quality in some metals, it is necessary to explore the atomic structure of metals versus non-metals.

At the atomic level the difference between metals and non-metals can be traced to both the number of valence electrons and the number of electron shells. By applying these two qualities to the known elements, the metallic character of an element decreases with the increase in the number of valence electrons. The metallic character, however, increases with the increase in the number of electron shells. The reciprocal of these two statements holds true for the non-metallic character of an element.

In other words, non-metallic characteristics increase with the number of valence electrons and decrease with the number of electron shells.

Let's review some basic principles of the structure of matter.

ATOMIC NUMBER - The atomic number of an element is defined as the number of protons in the nucleus. For each proton there is also an orbital electron. The orbits of the electrons are called energy levels. Each succeeding orbit outside the nucleus places the electron at a higher energy level.



Electron shells and the maximum number of electrons that may be present in each.

The outer shell electrons are called the valence electrons. An atom possesses the greatest stability when the outer ring of the atom contains eight electrons, except for the 1st ring which only has 2. Atoms attain stability by a rearrangement of electrons between them. The outer energy level electrons determine the chemical properties of atoms.

PERIODIC TABLE - The number of valence electrons increases from left to right and the number of electron shells increases down each column. Therefore, the properties of the elements become increasingly more metallic to the left and down.

Modified Covalent Theory has its basis on sharing of electrons between one or more atoms. These shared electrons then anchor the metal together and generate a metallic bond.

Band filling and band spacing determines whether a metal is a conductor, non-conductor or semiconductor. The Periodic Table is shown on page seven..

CONDUCTOR - has partially filled energy bands.

NON-CONDUCTOR - completely filled (or empty) energy bands with a large forbidden zone. Due to large energy differences between electron bands it is impossible for electrons to go from a lower energy band to a higher one. This inability to transfer electrons to partially filed orbits results in an energy gap known as a forbidden zone.

SEMICONDUCTORS - artificially introduced energy bands through lattice defects.

The best conductors generally make poor superconductors. Excellent high temperature superconductors lack a measurable degree of electrical conductivity.

The following metals have been found to hold the most promise for superconductivity. They are:

Barium
Gallium
Indium
Lanthanum
Lead
Mercury
Niobium
Strontium
Tin
Titanium
Vanadium
Yttrium

BCS THEORY

The BCS theory is based on low atomic activity in the superconductivity lattice structure in explaining how electrons can flow through a lattice without interference from other particles.

The theory claims that the electrons that flow through a superconductor travel in pairs, called Cooper pairs. These pairs are coupled by phonons which is like a subatomic glue. The pairs travelling through the lattice structure of the superconductor leave a wake which acts as a pathway through the atomic obstacle course for the other pairs to follow. The ability for the electrons to get through this maze without collisions with other particles is the reason for the zero resistance. If collisions occurred it would disrupt the flow and the superconductor would act like a normal conductor.

Above this critical temperature the atomic vibration within a material increases to the point where the lattice structure begins to vibrate too much.

This increased vibration causes the electron pairs to break apart and disrupt the phonon wake. This causes superconductivity to stop.

The vibrations are directly proportional to temperature.

At absolute zero there are no atomic vibrations.

As temperatures increase atomic vibrations increase. There are certain temperatures at which the vibrations become so large that atoms overcome the forces holding them in the lattice structure and they come apart. (Ice melting into liquid, water boiling and forming steam.)

No theory has yet adequately explained why superconductivity can take place at much higher temperatures. The Cooper pair theory, however, is believed to be the basis for superconductivity. How this can take place at the much higher temperatures at which superconductivity has been found may take years to theorize.

Is Superconductivity fact or fiction?

There is enough evidence that Superconductivity is here to stay and that it will change our jobs and our lives.

Application of Superconductors

Introduction

With the recent well publicized discoveries of superconducting materials that operate in the temperature range of liquid nitrogen rather than liquid helium, many are predicting wide-spread application of superconducting devices. This discovery has been dubbed "high-temperature" superconductivity. But since high temperature still means -290 deg. F, I'd call that almost a contradiction in terms, like government efficiency. It just shows that everything is relative. What these scientists call high temperature even a polar bear would consider positively frigid. So while researchers might predict wide-spread application of these devices, we might see efficient government before we see superconductivity in common use.

There are still fundamental barriers to what we would call wide-spread application of superconductivity. The first is the traditional economic limitation. The savings in manufacturing costs and the elimination of energy losses must more than compensate for the capital and operating cost of cooling the device to the balmy -290 deg. F temperature range. While liquid nitrogen cooling certainly improves the economics, it still severely limits distributed applications such as electric power transmission or transportation systems. I should note here that superconductors are only truly lossless with direct current. Using alternating current, superconductors still exhibit some magnetization hysterysis losses. So the superconducting devices that will be installed will require DC power supply.

Another impediment, noted in the discussion of material chemistry, is that these are ceramic materials. Like other ceramics, they are very brittle, and cannot be drawn or formed into wire using conventional production techniques.

Current Applications

With these limitations, the most immediate application of high-temperature superconductors will be in devices that now use helium-cooled superconductors. Most of these use superconducting magnets in medical imaging machines, such as magnetic resonance imaging and magnetic resonance spectroscopy, and electronic sensors, such as the extremely sensitive magnetic field detectors used in geophysical prospecting and submarine detection, and infrared sensors. These two applications comprise 75 percent of the current market for superconductors.

Other current applications include magnetic separators used in ore refining, physics machines such as atomic colliders and experimental nuclear fusion machines, and magnetic and electromagnetic shielding applications.

High temperature superconductors will make these devices relatively inexpensive, so that they can be deployed in greater numbers.

Potential Applications

A broader set of applications for superconductors are those for which there is proven technology, but no current commercial application. The improved economics of high-temperature superconductivity could help these devices find their way from the laboratory to the commercial marketplace.

While these include the use of superconductors in non-contact bearings, magnetically levitated mass transit, and computers, the area of greatest interest to us is in electric power generation, storage and transmission.

The potential seems to be greatest in power generation. One promising technology is Magnetohydrodynamic Generators or MHD. In a magnetohydrodynamic generator, a plasma, or hot ionized gas expands across a magnetic field produced by a superconducting magnet to generate electricity. Fouling and corrosion have been the major obstacles to the use of this technology. The potential for higher operating magnetic fields with the new superconductors is significant for this technology.

Conventional turbo generators and electric motors could also benefit from high temperature superconductors. The high magnetic flux density produced by a superconducting rotor field winding permits a great reduction in the amount of iron required in both the rotor and stator. Elimination of iron in the stator allows an increased density of turns to be cut by the rotating field, and also reduces insulation requirements. However, major problems must be overcome before the higher temperature superconductors are used, due to their brittleness. The very high magnetic forces and centrifugal forces require a stronger wire. The brittleness of the new materials makes this an extremely difficult production problem.

The application with perhaps the least obstacles to overcome is magnetic energy storage. The high cost of generating electricity has led to the development of load leveling energy storage processes, wherein excess electricity output during off-peak periods is stored to supply power during the time of peak demand. With superconducting magnetic energy storage, electric energy is stored as lossless direct current in a large superconducting coil. This yields a 90 percent efficiency which exceeds that of pumped hydro, batteries, flywheels, and air or thermal storage methods.

Such a coil was successfully tested at Bonneville Power System for 6 months in 1984. Because the new superconductors should reduce capital and refrigeration costs, superconducting magnetic energy storage looks more attractive.

The power application that might have the greatest impact on our business is also the one with the greatest barriers to commercial application: electric power transmission. For thirty years numerous projects were initiated to develop superconductor overhead transmission systems; the largest project being the Brookhaven National Laboratories 330 megavolt amperes test facility which operated for four years. Much was learned about losses in a complicated system that must be balanced against the cost of money. The major losses which form the load for the refrigerator, arise from three sources:

1) The current dependent losses of the conductor
2) The voltage dependent losses of the insulation
3) The heat leakage of the cryogenics enclosure containing the cables.

In addition, pumping losses must be considered when using long pipes. So while technically viable, power transmission may not be economically affordable.

Conclusion

In researching this topic, virtually all the available articles and papers on commercial application of superconductor technology sound like the song from "Fiddler on the Roof" - which kept repeating the words "but on the other hand." There are many technical and economic challenges that must be solved before the theoretical benefits of high-temperature superconductors can become a commercial reality.

Additional breakthroughs are required. These may come in the form of new manufacturing and production techniques. Another possibility is the development of novel applications. Virtually all of the applications currently envisioned for high temperature superconductors are extrapolations of devices already operated at liquid helium temperatures. The most important applications may involve devices yet to be contemplated, much less invented.

It is also possible that materials will be found that are superconducting at even high temperatures. One lab claims to have achieved superconductivity at 27 deg. F. Whether the required advances will be achieved in the next year or the next century is anybody's guess. As one researcher noted, "If you'd asked me a year ago if a liquid nitrogen superconductor was possible, I'd have said, 'Probably not in my lifetime.'"

Present Applications of Superconductors

A. Magnets
  1. Medical Diagnostics & Research
    a. Magnetic Resonance Imaging (MRI)
    b. Magnetic Resonance Spectroscopy (MRS)
  2. Radio frequency devices (gyrotrons)
  3. Ore refining (magnetic separators)
  4. Research and development
  5. Magnetic shielding
  6. Physics machines
    a. Colliders
    b. Fusion machines
    c. Radio frequency cavities

B. Electronics
  1. Sensitive accurate instrumentation
    a. Superconducting quantum interference devices
    b. Infrared sensors
  2. Electromagnetic shielding

Potential Applications

Proven superconducting technology, but no current market.

A. Power applications
  1. Energy production
    a. Magnetohydrodynamics
    b. Magnetic fusion
    c. Large turbo generators
  2. Energy storage
    a. Magnetic energy (load leveling coils)
    b. No loss portable electric storage batteries
  3. Electric Power Transmission

B. Transportation
  1. High speed trains
  2. Ship drive systems

C. Computers
  1. Semiconducting - superconducting hybrids
  2. Active superconducting elements

D. Electric Motors

E. Non-Contact bearings

PERIODIC TABLE

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
H 1																H 1	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 34	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mc 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po P4	At 85	Rn 86
Fr 87	Ra 88	**	Unq 104	Unp 105	Unh 106	Uns 107											

*Lanthanide Series	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
**Actinide Series	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

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