Superconductors

Introduction to Superconductors:

Before we can discuss the advantages, limitations and applications of superconductivity, we must first understand what superconductors are and how superconductivity works?

Superconductivity is a phenomenon whereby certain metals, metal oxides and ceramic compounds exhibit the property of zero electrical resistance when supercooled to a temperature near absolute zero.

For a substance to be superconductive it must be cooled to below its critical temperature (T_c). The critical temperature varies with the substance used. What this means, is that for a superconductive substance, once a current is set up in a closed circuit comprising only of superconductive wires, a current will flow forever. Many scientists have stated that superconductivity is the closest phenomenon to perpetual motion that we have discovered.

Superconductivity is essentially a *macroscopic quantum phenomenon*.

The Science of Superconductivity:

As of yet, there is no absolute complete theory of superconductivity. This can be attributed to the two types of superconductors.

The first, type 1 superconductors, were the first to be discovered and generally pure metals or metal alloys. These are also known as low-temperature superconductors due to the fact that the highest critical temperature of a type 1 superconductor is only 23.2 K. They are also often referred to as conventional superconductors.

Type 1 superconductors are explained using the Nobel Prize winning BCS theory proposed in 1957 by Leon Cooper, John Bardeen and Robert Schrieffer. The BCS theory states that electrons pair up in what is known as ‘Cooper Pairs.’ In a typical metal at room temperature, electrons are able to move throughout the lattice structure of metals, giving metals their conductive properties. However, due to the temperature, vibrations occur inside the lattice and this causes collisions between electrons and the lattice, causing resistance and a loss of energy. However, when a metal is supercooled, the lattice gets to a point (critical temperature), where the lattice effectively stops vibrating and the ‘Cooper pairs’ of electrons work together to overcome any remaining obstacles and avoid collisions. These two electrons work together to create a slipstream in much the same way that a car will be ‘dragged’ along a highway by a semi-trailer in front.

The second type of superconductors, known as type 2 superconductors or high-temperature superconductors are made commonly from ceramic compounds. The first and most common type of high-temperature superconductor is the YBCO ($YBa_2Cu_3O_7$) superconductor which was invented in 1986 and has a critical temperature of around 92 K. However, type 2 superconductors do not fit the conventional BCS theory of superconductors as they are not metals, and hence do not contain a lattice structure that would allow the ‘Cooper pairs’ to flow. For this reason, no total theory of superconductivity has been established.

The Meissner Effect and Magnetic Levitation:

The Meissner Effect is an effect whereby the magnetic field created in a superconductor will repel all other magnetic fields, regardless of whether they are changing or not. This means that if a magnet is placed over a superconductor it will levitate there inside the magnetic field.

The amazing fact about the magnetic levitation observed in superconductors is that even though the two objects repel each other, they are not pushed away entirely, but remain 'stuck' a certain distance apart. If two normal magnets' North poles where placed facing each other, the magnets would be pushed apart by a force that exists (even though minutely) to a distance of infinity.

However, a superconductor will repel a magnet a certain distance but then keep it at that distance. This is seen effectively in the video where, initially, the objects are kept apart, but when the magnet is lifted, the superconductor comes with it.

This is due to the way in which a superconductor sets up its magnetic field. When a magnetic field is created in a superconductor, poles are created to repel all fields.

The Meissner Effect is different from regular diamagnetism in that it repels all magnetic fields, not just changing ones. Unlike a regular magnet, which has just a North Pole and a South Pole, a superconductor can create many poles to ensure that all poles are repelled depending on what it is trying to repel. This same effect, however, is responsible for holding the magnet at a certain distance away. This is because when a magnet is pulled away from it, the poles are reversed to hold the magnet in place.

As a result of this effect, magnetically levitated (MagLev) trains are currently being trialled, mainly in Japan (see further down).

Advantages of Superconductors:

There are a number of advantages of using superconductors over regular conductors.

The first and most obvious advantage is the negligible energy losses that occur in superconductors as opposed to regular conductors. It becomes exceedingly more cost and power efficient if electrical devices can be operated with no resistance to the flow of electrons. They are therefore able to carry large currents for a long time with negligible energy losses as heat. In all testing carried out so far, superconductors have carried currents for years with no recordable losses.

They also have the potential to allow electronic devices to operate much faster and transport vehicles, such as trains, to reach speeds of up to 581 km h^{-1}.

Since type 2 superconductors were discovered after type 1, it is also of importance to compare the advantages of type 2 superconductors over their predecessors.

The obvious advantage of type 2 superconductors is their ability to operate at a much higher critical temperature than a type 1 superconductor. As a result of this advantage, many others flow on from it. The cooling agent used prior to 1986 was liquid helium, an expensive coolant but the only realistic option due to the low critical temperatures of type 1 superconductors. However, when the first type 2 superconductor was discovered that had a critical temperature above that of liquid nitrogen (77 K), superconductors became much more feasible option to explore. Liquid nitrogen is about 20 times more effective as a coolant than liquid helium and about one tenth as expensive, making type 2 superconductors more cost effective than the conventional superconductors. Table 1 shows a list of both type 1 and type 2 superconductors and their respective critical temperatures. It has also been discovered that some type 2 superconductors can be made from rare earth elements. These properties do have a number of foreseeable advantages for power grids, motors, generators and computers which will be dealt with below.

Table 1 – Critical Temperatures of various Superconductors

Substance	**Type**	**T_c (K)**
Rhodium	1	3.25×10^{-4}
Zinc	1	0.88
Aluminium	1	1.20
Tin	1	3.72
Mercury	1	4.15
Lead	1	7.20
Niobium-germanium	1	23.2
YBCO ($YBa_2Cu_3O_7$)	2	92
Thallium-Barium-Calcium-Copper Oxide	2	125
$HgBa_2Ca_2Cu_3O_8$	2	133
$(Hg_{0.8}Tl_{0.2})Ba_2Ca_2Cu_3O_{8.33}$ (Hg: 1223)	2	138

Limitations of Superconductors:

Despite many scientists believing that superconductors are the way of the future, there are still a number of limitations to their design.

The first of these is the restricted range for operating temperature. Since the world record for the highest critical temperature stands at 138 K, there is still a long way to go before superconductors are available to the average user at room temperature. It is impractical for handheld, consumer devices to have liquid nitrogen running through them.

Even if we decide to try and cool some devices continually with liquid nitrogen, it is very impractical to cool thousands of kilometres of underground electrical wiring connected to the power grid. More work must be done before they become a practical room temperature device.

Also, like most ceramics, type 2 superconductors are extremely brittle and therefore impractical unless methods are developed to reduce the brittle nature of these superconductors.

Type 1 superconductors, whilst not brittle, are not able to be cooled with liquid nitrogen (77 K) and their critical temperatures are nowhere near as feasible as their type 2 counterparts.

The other noticeable limitation to superconductors is the fact that they are quite sensitive to a changing magnetic field, meaning that AC current will not work effectively with superconductors. As a result, devices such as transformers, which only work with AC current, will be more difficult to implement into a DC oriented world when superconductors become a reality.

Possible & Current Applications of Superconductors:

Once the issues surrounding superconductors that are mentioned above have been resolved, superconductors have a wide range of applications they could be applied to.

One very promising development coming from the world of superconductors is the invention of the MagLev train. The MagLev train is a Magnetically Levitating train in which the train is kept 'on the tracks' by the magnetic field supplied by superconductors. The train effectively 'floats' over the magnets using the theory based on the Meissner Effect. Poles are set up on the track and also on the guidance rails so that the train is repelled from behind and attracted from in front.

The first MagLev train was developed in Japan in 1972 and Japan has been the leaders in levitated transport since. In 1990, the Yamanashi MagLev test line opened and has been operating ever since. The test line is an 18.4 km stretch of track that runs solely on the technology of superconductors. The MagLev trains are much safer, faster and environmentally friendly than their traditional counterparts. Japan is leading the way, continually investing more money into the further research of levitated vehicles. The MagLev trains that run on the Yamanashi test line have been clocked at speeds up to 581 km h^{-1}.

Another possible application of superconductors is in the use of SQUIDs. SQUIDs, or Superconducting Quantum Inference Devices, are ultra sensitive magnetic flux and magnetic field detectors. These devices are capable of detecting a change in a magnetic field as small as 1×10^{-14} T and have been linked to applications in quantum computers, geophysical surveying, MRI scans and ultra sensitive magnetometers.

Magnetic Resonance Imaging has been developed on the back of superconductor technology, and can be made even more sensitive by the implementation of SQUIDs into their design. MRI scans are made possible by the high powered superconducting magnets inherent in their design.

Superconductors could also be used to make electromagnets that generate massive magnetic fields with no energy losses.

Superconductors also have the potential to be implemented into the transmission and conversion of radio waves. Superconductors can be implemented into Ultra Wide Band (UWB) radio systems where all frequencies in a given 'band of interest' can be digitized at radio frequencies (RF). In other words, all the wave processing would be conducted in the digital domain, saving time, and also being more cost effective.

They have also been linked to use as particle accelerators, microwave detectors and filters for mobile phone base stations, and devices able to measure current, voltage and magnetic field strength with unprecedented accuracy.

The applications of superconductors also have potentially big effects on computers, generators & motors, and electricity:

Computers & Electric Devices:

The integration of superconductors into computers could have a big improvement in the speed, capacity and performance of all computers and electric devices ranging from household devices to powerful supercomputers.

Due to the negligible resistance of superconductors, computer processors could run at speeds in excess of 120GHz. This means that computers running on superconductor technology could run 30 times faster than current designs. Also as a result of no resistance, the processors are able to run not only at high speeds but also using less power. In fact, the power level of a superconductor microchip is 100,000 times more efficient than its silicon predecessor.

SQUIDs, if implemented into computing, have the potential to allow computer manufacturers to begin mainstream release of quantum computers.

Superconductors also have the ability to improve the amount of hard drive space available to the average consumer by implementing the technology into hard drives as well.

All the advances in computer speeds are made possible by the theory of the Josephson Effect. The Josephson Effect is an effect observed in superconductors that are joined. When superconductors are joined by a thin, insulating layer, electrons are able to pass through much more easily. It is this theory that has made the potential for super fast electrical switches in computers a possibility.

Motors and Generators:

Currently, the production of electricity in generators is exceedingly inefficient when it comes to energy losses throughout the entire process.

Because superconductors would have significantly lower energy losses during the generating phase, significantly less coal and other fossil fuels would be required. Generators that are wound with superconducting wires could generate the same amount of energy as conventional generators using significantly smaller equipment with less energy losses. In fact, superconducting generators have been theorised to be 99% efficient.

These same properties can then be applied to electric motors, where there is little energy losses throughout the process. Currently, motors that have been made using superconducting technology have reached 5000 horsepower engines. Future motors could be produced without an iron core making them not only more space efficient but also lighter and more portable.

Electricity and the Power Grid:

Perhaps the field that will benefit most from superconductor technology is in the transmission, generation and storage of electricity.

Firstly, the superconducting technology would allow for the beginning of fusion power. Fusion requires large electromagnets in order to contain the immense power produced. Superconductors could be used as part of those electromagnets.

In regards to the storing of electrical energy, superconductors can be applied to Superconducting Magnetic Energy Storage Systems (D-SMES). These systems are capable of storing upwards of 3 million watts of power.

But when it comes to the transmission of electricity through the power grid, this is where superconductors can have arguably the biggest impact. If we were to implement superconducting technology into the power grid right now, the liquid nitrogen cooled cables could be placed underground in place of copper cables. These superconductor cables are 7000% more space efficient than their copper rivals. These new power lines effectively have negligible energy losses, reducing the need for boosting of voltage at substations. By using superconducting electrical cables as opposed to copper, the cost of the transmission is reduced and very large current densities are able to be transmitted with 3 to 5 times the current of regular wires. The only concern with this, as mentioned previously, is the practicality of cooling kilometres of underground cables.

Future Directions for Superconductors:

It is becoming increasingly obvious to scientists all over the world that superconductors are the future in terms of transmission and applications with electricity.

There may come a time when power storage devices, electric motors and electronic devices run on the science of superconductivity and the human race is transported around solely on magnetically levitated vehicles, but scientists have a lot of work ahead before this becomes a reality.

To make superconductors a feasible option for world electrical devices, scientists must put their effort into a number of key problem areas.

The first of these is getting superconductors to work at room temperature. This may entail creating devices that contain a cooling agent or it could mean that scientists need to find new compounds that work at even higher critical temperatures than those currently available.

Another issue that will need to be addressed is ensuring that they are not as brittle as in current designs. Finding some additive or substance that has the ability to increase the strength and durability of a superconductor without affecting its superconductive nature is another area that scientists will be looking to solve in the future.

But, realistically, before we can find real solutions to these problems, it is imperative that an accurate and plausible theory of superconductivity for type 2 superconductors is established. Either that, or finding some complete theory that covers all aspects of superconductors.

However, once these problems and limitations have been overcome, the future of superconductors opens up. Whilst there have been many applications of superconductors mentioned previously, some of these are not feasible yet.

The 120GHz household computer will become a reality only once the limitations have been overcome, as will the Ultra Wide Band (UWB) radio systems. The future of superconductors in our world may include all electrical wiring and power lines being made from superconductors, and the entire human race travelling on magnetically levitated transport vehicles.

MagLev trains, whilst being used currently, are not yet used everywhere due to the initial expense. When governments are willing to put in the initial funds or cheaper methods are found, only then will MagLev trains become a reality.

Whilst magnetically levitated trains are a realistic option right now, what about other forms of transport that superconductors could be incorporated into?

One such possible future direction is in the development of a MagLev highway for regular passenger cars. The cars would use the same technology that keeps the MagLev trains ‘floating’ above the track. The propulsion system would also work similarly to that of the MagLev train.

However, unlike trains that follow the same track everyday, cars need to be able to turn as well. For this reason, the steering wheel would need to have direct input into the magnetic poles of the superconductors on either side of the car. For instance, when the car puts a blinker on to change lanes, the poles on the right side of the would change or disappear entirely to allow the car to first be attracted towards, and then cross the centre line.

For this to work, the entire highway would have to have some system in place so that it could create magnetic poles (using superconductors) to attract the car in the right direction.

Not only would this system allow cars to travel faster, there would be no need for an internal combustion engine, decreasing our dependence on fossil fuel resources. And since the edges of the roads could have repelling magnetic poles, crashes where drivers go off the road or onto the wrong side of the road could be eliminated. Also, by incorporating magnetic poles created by superconductors on the front and rear of the vehicle, front and rear end collisions could become a thing of the past. Of course, initially, vehicles may have to have wheels for street driving, but superconductors for driving on highways that use the technology.

Whilst all this sounds at first a little far fetched, we have the technology with the potential to make it happen, it just becomes a matter of whether a government is willing to invest the initial money.

Superconductors also have the potential to be involved in the creation of the first fusion power plants. To control the enormous amounts of energy produced during fusion reactions, high powered electromagnets are required with extremely strong magnetic fields. For this reason, superconductors have been linked to a future application in fusion power plants.

So while superconductors are a very viable future solution in so many applications, much work must be done before it becomes feasible.

This means that scientists face a dilemma in getting the near perfect world of superconductors out of the laboratory and into the household.