A hope for superconductivity

The depletion of fossil fuels and transition to renewable energy resources gives hope for superconductivity and superconductivity gives hope for surviving the looming energy crisis and solving global problems facing human society. **Pavlo Mikheenko** explains why superconductivity is important and how it is going to enter our everyday life.

Next year superconductivity will celebrate its 100^{th} birthday having become deeply engrained in scientific and technological life. Still for many people it is an exotic phenomenon hardly having any importance. Some could vaguely remember that it has something to do with low temperatures and somehow allows electrical current to flow without resistance. Others may recollect a strange effect of levitation of a magnet above the superconductor and that is probably all.

More curious people might know that temperature can be measured in Kelvin (K), where zero Centigrade (ºC) equals 273 K and that superconductivity occurs at only a few Kelvin. Indeed, it was discovered by Kamerlingh Onnes in 1911 when temperature as low as 4.2 K was reached for the first time. A progress in materials pushed the critical temperature (below which superconductivity occurs) up to about 20 K and it stayed there for years. There were even theories suggesting that superconductivity couldn't persist at temperatures above 20 K.

A breakthrough came in 1986 when high temperature superconductors (HTS) able to work at the boiling temperature of liquid nitrogen (77.3 K) were discovered. In the following boom of financial support for superconductivity a quick revolution in technology was expected. The main argument for this was the exceptional effectiveness of superconductors in variety of applications and a low cost of liquid nitrogen (about 30 pence per litre). There is a good reason why people do not remember this revolution. It did not happen. It was prevented by a seemingly minor but formidable obstacle - the grain boundaries within HTS materials. It appeared that supercurrent couldn't cross even low-angle HTS grain boundaries and so to make HTS tapes and wires functional, one would need to perfectly align their crystal lattice, which is neither easy not cheap.

The revolution was replaced by evolution, which eventually led to a cost-effective production of HTS tapes and wires. However, critical current density in these tapes and wires is still not satisfactory and their thickness is restricted to a mere few micrometers.

Surprisingly, another revolution is possible, but not quite the one that was expected in 1986. It is driven not by a desire to improve our lives, but by the necessity to survive. It is obvious that human society faces global problems of over-stretched natural resources, disappearing fossil fuels and massive CO_2 emissions leading to global warming. A large part of these emissions comes from transport. Therefore, a reasonable measure to prevent global warming would be to use a clean fuel derived from the renewable resources. This fuel is already found. It is hydrogen, the most abundant element in the universe. The practical question is in what form to use it. The compressed gas requires heavy cylinders. In the solid-state storage devices hydrogen comprises only a small fraction of the weight. Liquid hydrogen requires proper thermal insulation and rather expensive cooling. Its low temperature (20 K) may be considered as an obstacle, but in fact it is a great advantage. It accesses the world of superconductivity with implications well worth the cost of hydrogen liquification.

Although some superconductors are functional in easier-to-produce liquid nitrogen, the use of this liquid as a coolant for global applications of superconductivity would be a wrong choice. For example, the cost of liquid nitrogen for a pipeline built to cool a superconductor stretching from London to Cairo, with a diameter of pipe of about 1 meter, would be about £ 1,000,000,000. This is lost money because the liquid nitrogen could function only as a coolant, whereas, if the super-grid is filled with liquid hydrogen, it would also provide a global energy store in which every bit of hydrogen could be used as a fuel.

Drivers of the hydrogen economy

The wide use of superconductors is driven by the transition to a hydrogen economy, which is an effective response to limited deposits of fossil fuels and uncontrollable greenhouse emissions leading to global warming. On the other hand, it is hydrogen abundance, availability and suitable chemical properties that allow its use in circulation of energy.

The driving forces for the hydrogen economy are ecological, technological and political. It is likely that governments will heavily tax any use of fossil fuels for energy needs and financially encourage more effective use of energy. It is here where the superconductivity comes into action with its use simplified by the abundance of liquid hydrogen.

Superconducting materials for hydrogen economy

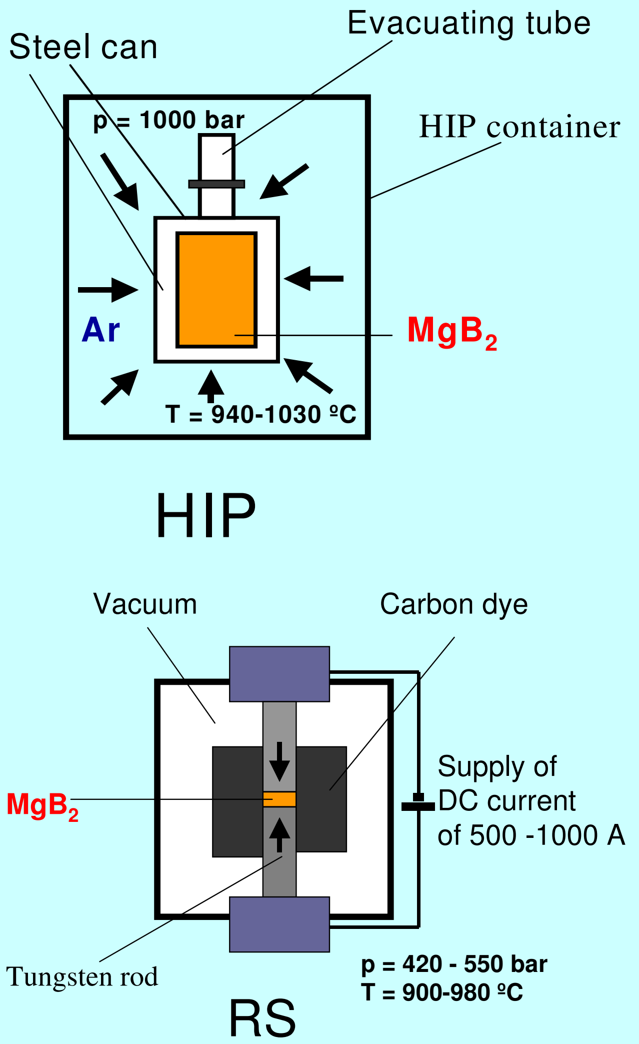
There are many superconducting materials that can work in liquid hydrogen, all of which were discovered after 1986. HTS is a suitable class of materials for liquid hydrogen applications. Although HTS materials are extremely sensitive to grain boundaries and show unsatisfactory performance at 77.3 K, they perform much better in liquid hydrogen and there is also a good progress in development of cost-effective methods for alignment of HTS.

So far the best material for hydrogen applications is MgB_2. Its superconductivity was discovered in this decade, in 2001. Its critical temperature is twice the boiling temperature of liquid hydrogen and it is the only known material having a critical temperature well above 20 K and no grain boundary problem. Other materials include fullerenes and recently discovered iron-based pnictides. There is no doubt that more materials suitable for hydrogen economy will be synthesised.

Beauty of MgB_2

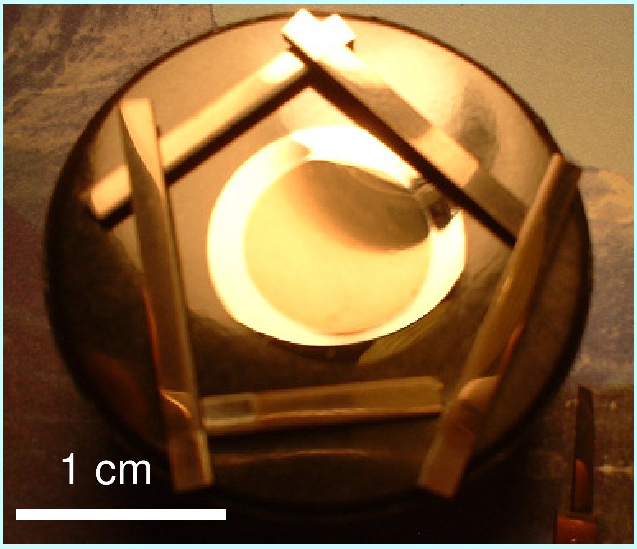
MgB_2 is an overlooked superconductor. For about 50 years before its emergence as a superconducting material, it was available on chemist's shelves as unattractive black powder commonly used for synthesis of other materials, including superconductors with low critical temperature. Properly prepared by advanced techniques such as Hot Isostatic Pressing (HIP) or Resistive Sintering (RS) schematically shown in figure 1, it is an exceptionally attractive, light, gold-like material. Figure 2 shows this material in the form of iron-sheathed disk (centre) and small bars. It would be the dream of an alchemist to create a gold-like material from a black powder and in fact the strategic value of this material is like that of gold.

1 Advanced methods for preparation of MgB_2



Schematics of hot isostatic pressing (HIP) and resistive sintering (RS). The material in the centre is MgB_2. The processing parameters such as pressure, temperature and electrical current are shown in the plot. The arrows indicate direction of pressure. These relatively simple methods allow obtaining polycrystalline MgB_2 with nearly single-crystal mass density. The multiple grain boundaries formed during the pressing provide strong pinning and high critical current in the material.

2 Hot isostatically pressed MgB_2



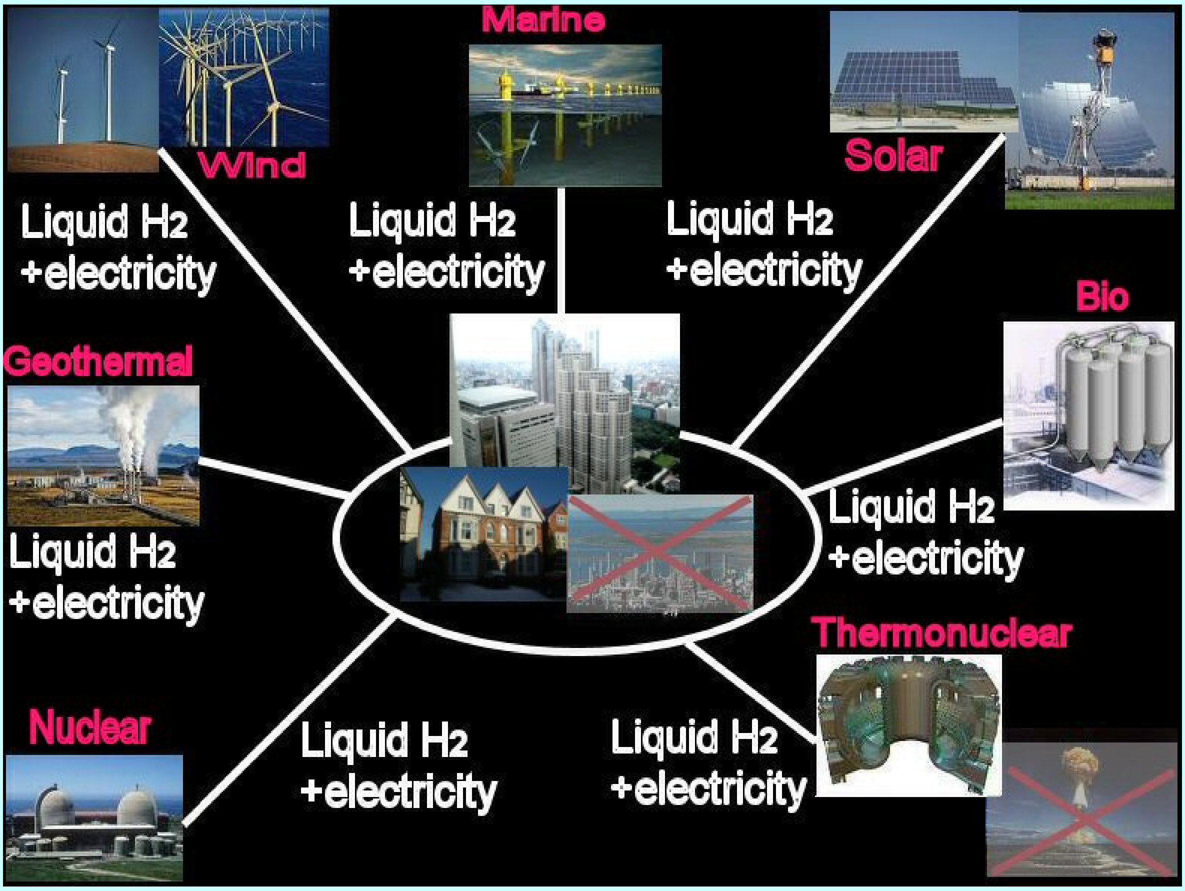
MgB_2 produced by hot isostatic pressing is in the centre of bakelite disk. It is a shiny gold-like material surrounded by the stainless steel ring. Several bars are cut from the pressed MgB_2 and placed around the polished MgB_2 disk in a form of pentagon. MgB_2 is a hard material three times lighter than stainless steel.

The main attractive features of MgB_2 as superconductor are high critical temperature (~40 K, twice the boiling temperature of liquid hydrogen), high critical current density (up to 10^6 A/cm^2 at 20 K) and low mass density (2.62 g/cm^3). The most important application for MgB_2 is expected to be the infrastructure of the global hydrogen economy, which will be composed of superconducting MgB_2 pipes simultaneously delivering liquid hydrogen and loss-free electricity. In the global superconducting delivery system of the future shown in figure 3 liquid hydrogen and electricity will be supplied from the renewable resources: wind, marine, solar, geothermal, biological plants and also from the nuclear and thermonuclear stations. There will be a few large input ports for large amounts of hydrogen and electricity and many small outlets delivering fuel and energy to users.

Infrastructure for hydrogen economy

The general energy distribution concept for a hydrogen economy is already known as SuperGrid. In the first design of SuperGrid, HTS wires were suggested for the transport of electricity (see, for example, Physics World, volume 22, No 10, October 2009, p. 37). The recent designs of SuperGrid are based on MgB_2 as a cheaper alternative to HTS. The SuperGrid is still a concept and currently there is no technology to produce large-cross-section and long-length MgB_2 needed for the pipelines. One of the solutions would be to upgrade HIP to hot hydro-extrusion. The thick-film MgB_2 technology for covering surface of metal pipes is also possible.

3 Infrastructure for hydrogen economy



Global infrastructure for the hydrogen economy will be composed of superconducting MgB_2 pipes simultaneously delivering liquid hydrogen and loss-free electricity. The liquid hydrogen and electricity will be derived from the renewable resources: wind, marine, solar, geothermal, in biological plants and nuclear and thermonuclear stations. Few large input ports supplying large amount of hydrogen and electricity will be combined with multiple small outlets delivering fuel and energy to users. Heavy fossil-fuel processing plants will not be necessary.

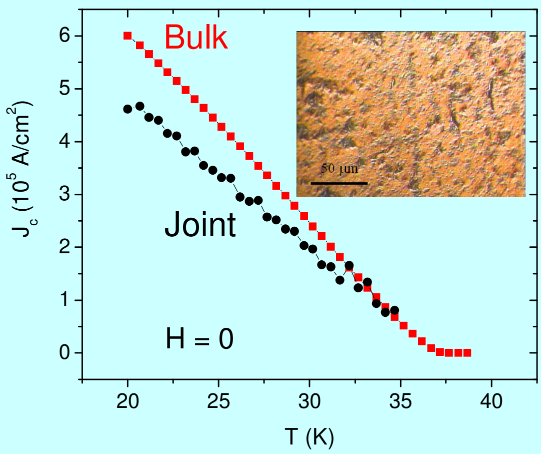
A MgB_2 pipe of the inner diameter of 18 centimetres and the outer diameter of 20 centimetres can easily transfer the power of an average power station (460 MW). Such a pipe could be made by hot hydro-extrusion. Its small size could be ideal for moving electricity from power stations to cities. However, its diameter would be insufficient for the delivery of liquid hydrogen. A large-diameter pipe specialising in delivery of hydrogen could be made by thick-film technology. An invention of the author of the paper is an MgB_2-based superconducting paint. Simple painting of a metal pipe with this paint and subsequent thermal treatment produces thick superconducting cover. This paint has already been tested.

The suggested infrastructure would be flexible. For example, in daytime, when demand for electricity is high, it could mainly be used for the delivery of electricity. In the nighttime, considerable part of electricity would be re-directed for the production of hydrogen (e.g. by splitting water) and resulting hydrogen would be liquefied and transported in large quantities to be used as a fuel in the morning.

The paint technology is intrinsically free from the superconducting joint problem. However, small-diameter hydro-extruded pipes may require joints. A technology for large-area superconducting MgB_2 joints that was developed in Birmingham (UK) might clear the way for this application. To illustrate the properties of the joint, figure 4 shows the temperature dependence of critical current density of the joint and bulk MgB_2 material adjacent to it. The nanoparticles were added to this MgB_2 to increase its critical current. There is only a small decrease in the critical current density in the joint in comparison with bulk MgB_2. Currently only a few joints have been produced and further improvement in critical current is possible. The inset shows an optical image of the joint (vertical line across the middle of the sample). The MgB_2 used in this experiment was produced from a cheap low-grade powder. In spite of relatively large number of pores and inclusions (dark areas) the critical current density is high, which enables cost-effective applications of MgB_2.

The SuperGrid infrastructure is designed for the carbon-free economy since burning hydrogen produces only water. Unexpectedly, the large-scale production of MgB_2 offers another possibility to tackle CO_2 emissions. A disadvantage of pure MgB_2 comparable to HTS is its relatively low critical magnetic field. This would strongly restrict its in-field applications. A way to increase critical field is already known - the incorporation of a small amount of carbon into the crystal lattice of MgB_2. A specific way of adding carbon is to mix hydrocarbons with MgB_2 powder. During thermal treatment hydrocarbons decompose, carbon enters the crystal lattice of MgB_2 and is trapped there permanently (no CO_2 emission, no necessity for CO_2 storage) while hydrogen is released and can be collected, liquefied and used as a fuel. This could be one of the most effective ways of decomposing hydrocarbons. With well-developed MgB_2 powder metallurgy producing thousands (possibly millions) tons of MgB_2, this process would significantly reduce emissions of CO_2 from otherwise burned hydrocarbons.

4 Superconducting MgB_2 joint



Temperature dependence of critical current density of the joint (black) and bulk MgB_2 (red). There is only a small decrease of critical current density in the joint. The inset shows optical image of the joint. It is vaguely seen as vertical line across the middle of the sample.

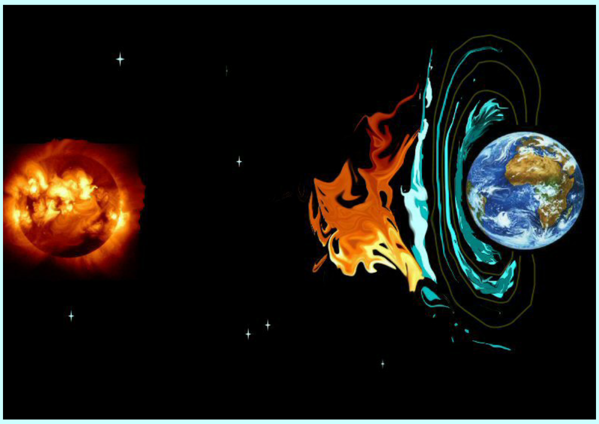
Global applications of superconductivity

When the supply of liquid hydrogen is secured, superconductivity will enter everyday life. It could start with car manufacture. There are already several models of cars using liquid hydrogen, among them BMW Hydrogen 7. The tank of the car typically contains more than 100 litres of liquid hydrogen. The obvious question is: when liquid hydrogen (with its low temperature of 20 K) is already there, why not make a fully-superconducting car? It can feature highly efficient superconducting motor; superconducting generator to cover all electrical needs of the car; loss-free superconducting wiring; superconducting current limiter protecting electrical system of the car; superconducting (possibly quantum) computer etc. And why only superconducting car? Why not fully superconducting train, plane, ship, submarine, spaceship? Why not make a Superconducting Home Energy Unit? This unit can contain some 200-300 litres of liquid hydrogen and include superconducting generator, current limiter, computer and other efficient superconducting devices.

The house would be self-sufficient in energy for some time and immune to blackouts. If a blackout is not that important for a house, it is of vital importance for the hospitals, defence installations, municipal buildings. The size of the market for these applications would be immense.

When the large-scale supply of liquid hydrogen is secured, the global problems might be addressed. One of the problems is magnetic protection of the Earth. Our planet is lucky to still have magnetic protection (figure 5) while unlucky planets like Mars and Venus already lost it. Mars could possibly have harboured life when it was protected from the solar wind by its magnetic field. However, because of the collapse of the field due to cooling of the planet its atmosphere was partially blown off and instead of possible green paradise Mars became a cold hell. A hot hell is Venus, which is closer to the Sun than Mars and Earth. Unfortunately Earth's magnetic protection is limited. Our planet's core is cooling (in spite of global warming) and at some moment the circulation of molten lava inside the Earth will stop and its magnetic field will collapse.

5 Magnetic shield against solar radiation

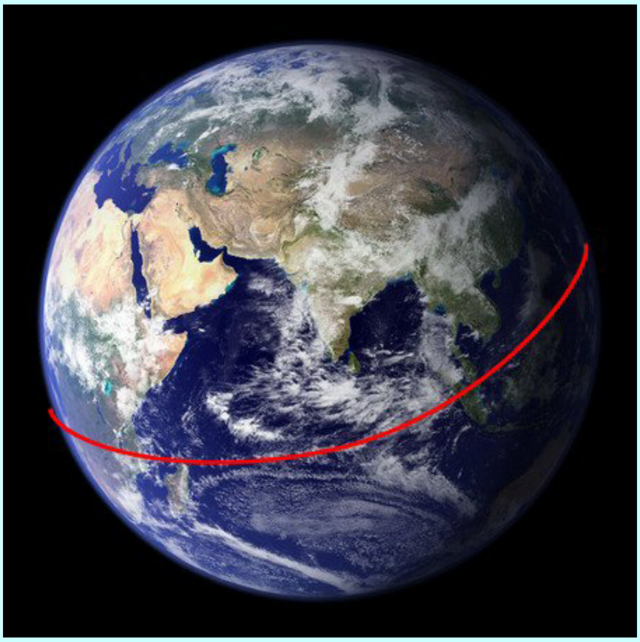


Natural magnetic field protection of the Earth against solar radiation. The screening of Corona Mass Ejection is schematically shown.

It may not happen soon, but there is another worrying process, reversal of magnetic poles. In the last 10 million years it happened 40-50 times and we are close to the next reversal, estimated for about 1500-1600 years time. During the reversal Earth would be, for few years (or tens of years), without sufficient magnetic protection. Some atmosphere would be blown off, cancer diseases would spread and plant growth would be inhibited. The exact consequences of being without protection a short time are not clear, but they are not pleasant. Though it is clearly a problem, it seems humans can do nothing about it. The processes taking place in the interior of our planet cannot be influenced. The satellite monitoring of the magnetic field is the only reasonable activity suggested so far.

It is true that we cannot influence processes inside the planet, but we can protect it magnetically. Let us imagine superconducting MgB_2 pipeline created around the planet as shown in figure 6. A superconducting current in this pipeline would create magnetic field matching today's planet field. A normal conductor would not be suitable for this purpose because the induced current would quickly decay, whereas the superconducting current flows without decay (a basic property of superconductors). The value of current, which is necessary in the pipeline to maintain a magnetic field of 0.5 Oe (the magnitude of the magnetic field close to the surface of the Earth now) is about one billion amps. It seems a very high current, and it should be below the critical current of the pipeline not to suppress superconductivity in it. However, at the already achieved critical current density of 10^6 A/cm^2 in MgB_2, a cross-section of just 32 cm by 32 cm would be sufficient. The superconductor of this cross-section should be distributed on the surface of a pipe of a large diameter to not suppress superconductivity by its own magnetic field.

6 Superconducting pipeline for magnetic protection of Earth



Artificial magnetic field protection of Earth against solar radiation using superconducting liquid hydrogen-cooled MgB_2 pipeline (red).

One would think that a large number of power stations are needed to induce such a large current in the pipeline. In fact, power stations are not needed at all.

In addition to carrying current without decay, the superconductor repels magnetic flux. If the superconducting equator were built now, due to the repulsion the present magnetic flux would not be able to escape closed superconducting loop and the Earth's present magnetic field would be permanently safeguarded, remaining as strong, as it is now.

One would say, wait a minute, what about the processes inside the planet? They continue their way, but with the superconducting equator they are unable to change Earth's magnetic field. Instead they induce current in the pipeline and the maximum value of this current will be twice that which is necessary to maintain 0.5 Oe by the equator itself.

Since the direction of the magnetic field around the planet is not important for humans, this current might be redistributed to smaller superconducting rings. The magnetic poles would then reverse, and a large amount of energy would become available in the form of current in these rings. This current could be used in kettles, stoves, for industry needs and for scientific experiments. It is not a huge amount of energy, but it would be enough for a country such as UK for about one year.

It is a new method of energy generation. Unfortunately this energy would be taken from our planet accelerating its cooling (eventually high current should be kept in the ring to protect the planet when molten current inside will cease to flow). The reversal of poles is also a rare event, taking place once in about 200,000 years. However, every 11 years Sun activity changes and it sends to Earth large amount of charged particles. These particles interfere with the magnetosphere and induce large currents in the power lines, sometimes burning them down and causing blackouts. The superconducting loops would trap this current making it usable. The largest magnetic activity caused by Sun is in the areas close to the magnetic poles, where large voltages are induced even on the gas pipelines. That is why it is reasonable to install superconducting pipeline rings there.

The energy we would get from these pipelines is renewable energy (as long as the Sun is active) and is not much different from the renewable energy we get from sunlight. The difference is only in the frequency of electromagnetic waves or the rate of change of electromagnetic field. The large superconducting loops are able to get energy from the slowly changing magnetic field. The origin of the magnetic field may also be external to the Solar system. In its motion through the space, Earth may cross the zones of strong field and get energy from them.

One of the obstacles for such global projects would be insufficient amount of material to build them. However, constructing the superconducting equator described would require only 5 million tonnes of Boron, 0.00015% of the estimated reserves in the upper 1 km of the Earth's crust. At the current rate of mining, the required Boron could be procured in 5 years.

A way to extract energy from our planet may help to deal with another global problem, even more serious than reversal of magnetic pole. This is an eruption of a Supervolcano. The Supervolcano in Yellow Stones National Park, USA is erupting with periodicity of 800,000 – 600,000 years and 640,000 years are already passed after the last eruption. If it happens, Earth will be covered with thick cloud of ash for several years. Crops will fail and most of the human population will be wiped out. A possible solution would be to surround the active volcanic area with a superconducting pipeline as shown in figure 7. On the brink of eruption, due to changes in the circulation of lava, there will be a change in the magnetic permeability of the volcanic area. This will induce current in the pipeline. Removing this current would mean removing energy from the Supervolcano. If sufficient amount of energy were removed, such local 'surgery' could prevent an eruption. In the future, when it would be possible to install and control current in many superconducting loops, the motion of molten lava in the interior of Earth would be controlled on a global scale reducing its amount in most dangerous places close to the surface of the planet.

The large superconducting loops could also contribute to deflection of meteorites, another danger threatening civilisation. Most of meteorites contain iron, nickel or both. They are either magnetic or can be magnetised. The repulsion between a superconductor and a magnet could be used for the deflection. Moreover, during the deflection, part of the energy of meteorite could be trapped in the superconducting loops. Some meteorites may even be welcomed to our planet to get energy from them.

7 Extraction of energy from a Supervolcano

Superconducting pipelines forming a loop around a volcanic area could be used to extract energy from and prevent the eruption of a Supervolcano. The local volcanic 'surgery' may be a realistic concept.

The global magnetic protection of Earth may be currently non-realistic due to insufficiently developed technology or because of political reasons. However, protection can be implemented locally, around big cities or even on smaller scale around important installations. It would be reasonable to begin with the protection of satellites. MgB_2 is a light superconductor and due to the low temperature of Space, it will work without cryogenic liquid. The MgB_2 paint could be used for this purpose. Especially convenient would be to use paint on the Moon or on the orbit of Earth, where thermal treatment in oxygen-free atmosphere would be especially effective.

Conclusion

In conclusion, the disappearance of fossil fuels, global warming and the transition to renewable energy resources give hope to superconductivity and superconductivity gives hope to cope with threatening energy crisis and address global problems facing human society on our planet.

Acknowledgment

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