SUPERCONDUCTIVE LEVITATION AND PROPULSION COILS OF SCMAGLEV TRAINS

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***Abstract*—** *The use of superconductive magnetic coils to levitate and propel magnetic levitation (maglev) train systems by Superconducting maglev (SCMAGLEV), developed by the Central Japan Railway Company, is revolutionizing transportation. Placed in strategic locations on the bottom and sides of train bodies and along tracks, these magnets repel each other, and levitation is achieved. Active coils of superconductive wire that does not resist high electric currents allow a great magnetic field to be generated, and by controlling the direction and magnitude of the current, the train is propelled.*

By levitating a train, this transportation mode no longer requires physical contact with a surface. This is important because almost no energy that should be propelling the train forward is lost to friction. Thus, the SCMAGLEV trains that use this technology can currently travel up to 603 km/hr. Maglev technology could improve the daily commute to work in other cities for businessmen and consultants. For example, even in this developmental stage, over 30,000 individuals have ridden on the Yamanashi train since 2014, all providing positive feedback about their experience. Superconductive levitation and propulsion coils of the SCMAGLEV provides a possibly sustainable future of transportation in which billions more can participate.

Key Words— Coils, Electrodynamic Suspension, Lorentz Force, Rare Earth Metal, SCMAGLEV, Superconductivity

A RADICAL IDEA

On December 24, 1801, British inventor Richard Trevithick introduced the first steam powered locomotive vehicle to the world [1]. Since then, millions of loads of passengers and cargo have used this revolutionary technology to move across continents. As innovation continued, older designs of trains became obsolete, and the train was constantly improved. In 1963, the possibilities for the railed vehicle took a radical turn. Dr. J. R. Powell of Brookhaven National Laboratory proposed a transportation system based on the concept of superconductivity. Proving to be too costly, the system went under revision by Powell, along with colleague Dr. G. R. Danby, and in 1966, their paper "High-Speed Transport by Magnetically Suspended Trains" was presented [2]. This proposal was based on three main concepts: "(1) superconducting coils are arranged on the vehicle while normal conducting coils are installed on the track; (2) the vehicle is lifted by electromagnetic induction…; and (3) null flux used for vehicle guidance" [2]. Essentially, magnetic levitation (maglev) technology would replace the conventional form of locomotive train with magnetic repulsion to propel the train. Traditional locomotive trains ride on tracks and are propelled by a gasoline or other combustion engine whereas maglev trains use magnetic forces to levitate above a track and to propel itself.

In 1973, Japan devised a basic plan to implement this idea to connect its cities of Tokyo and Osaka based on its 1970 Shinkansen Railway Development Act. In 2009, the Transport Policy Council finally reported that it would designate the Central Japan Railway company as the operator and constructor of the project and that Superconducting Magnetic Levitation (SCMAGLEV) technology would be used in a route through the Southern Japan Alps [3].

Approximately 85,700 passengers rode on Amtrak trains daily from October 2015 - September 2016 [4]. It is clear that standard train travel is not dead. What is less clear is how sustainable it will be for the years to come.

Sustainability has three main factors: social, environmental, and economical. Social sustainability is the ability of a project to enhance the quality of life for people and facilitate community development. Environmental sustainability is the conservation of natural resources and preservation of local ecosystems. Economical sustainability is the cost-benefit analysis of the project in question.

The SCMAGLEV is a possibility for this next age of transportation. The focus of this paper is to discuss the operations and the sustainability of the technology that makes it all possible: superconductive levitation and propulsion coils.

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SUPERCONDUCTIVITY

Maglev technology is made possible through the use of superconductive coils to generate enough electromagnetic force to levitate an extremely heavy load. An electrical coil is a cylindrical coil of wire. When current is run through a coil, a magnetic field is created. By arranging coils of similar polarity, north and north, a force of repulsion is created. This force of repulsion is enough to suspend the train above the track; however, this amount of levitation is not possible with ordinary electromagnetic coils.

Electrical resistance of a coil is defined by Ohm's Law as the voltage through a wire per the amount of current through the wire. To maximize the force created by the coils, the current running through the coil must be maximized and maximum current is achieved by minimizing resistance. The material in which the conductor is created, the length of the wire, and the surface area all affect the resistance of the of the wire. Therefore, if a coil reaches a state of superconductivity, then the force will be optimized.

Superconductivity is a state in which a coil has zero or negligible resistance and without any resistance, the coil can provide more force. For this state to be reached the temperature of the coil must be decreased drastically to a temperature near absolute zero, -273.25 °C. The BCS Theory, BCS from the scientists, John Bardeen, Leon Cooper, and Robert Schrieffer, states that supercurrent is not carried by individual electrons but instead a single quantum state. At a critical temperature for superconductivity, the atoms move minimally relative to each other, allowing for unconventional properties to be seen in the electron cloud [5]. This is because paired electrons can form a boson, which is defined as two particles which are in the same quantum state. Normally when pairs of electrons are present, they must follow the Pauli Exclusion Principle, which states that no two electrons can have the same four quantum numbers in a single atom and the spin direction in each orbital must be different. However, as a boson is formed, electrons at a supercooled temperature can act different than conventional theory. Paired electrons, bosons, can condense in to the same energy level [6]. When reaching a state of conductivity, within the coil, a condensate is formed. This means that at such low temperatures, the atoms hardly move relative to each other because of limited free energy in the material [7]. Therefore, as a negatively charged particle passes by positively charged particles, the lattice structure of the material is deformed inward towards the negative charge as displayed in Figure 1.

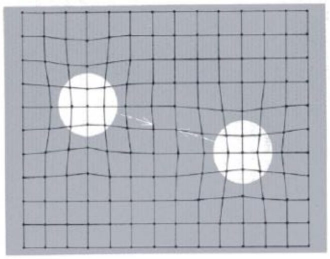

FIGURE 1 [8]
Potential Wells in a lattice structure

The deformed area formed area is a potential well; therefore, the electrons attract towards each other instead of repelling. As the deformation occurs, an area of increased positive charge is created which attracts more electrons, creating larger deformations and more attraction between deformations [9]. At this state the atoms begin to clump together and enter the same energy state across the entire material. The group of atoms begin to act as if they were one atom [7]. Current, or the flow of charge, through a given material, is transferred between atoms through atomic collisions, but if the particle is acting as one atom, charge flows unimpeded by collisions. With normal collisions, some energy is used for a thermal exchange between particles in order to maintain a free energy to allow particles to move within the system; however, once acting as a superconductor, no energy is lost for entropy of the system [10]. This equivalates to zero resistance within the material because all energy can be transferred as current.

FORCES

The forces which cause the train to be levitated and propelled down the track are electromagnetic forces, more specifically, Lorentz Forces. The Lorentz Forces created by the coils are dependent on the velocity of an electron passing through the wire and the magnetic field. The relationship is explained through the equation:

$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

where F is force, q is charge, v is the velocity of the charge, and B is magnetic field. F, v, and B are all in bold to indicate that they are vector quantities. When current, or a flow of charges, is run through a wire, a magnetic field is created. The direction of this magnetic field comes out perpendicular to the surface of the wire and is directed from the north pole of the induced dipole, which acts like a magnet, to its south pole. An individual charge flows through the magnetic field and is perpendicular to the magnetic field. The cross product dictates a force vector perpendicular to both the magnetic field and the velocity of the charge. The magnitude of the forces varies according to the amount of charge, the velocity of charge, and the strength of the magnetic field. Since the force created by the magnetic field has a specific direction, the arrangement of coils specifically on the train will be pertinent to levitating and propelling the vessel.

Furthermore, when a coil is transitioning to a superconductive state, a phenomenon called the Meissner Effect occurs. Within a conducting coil, there is an internal magnetic field present that is caused by the movement of electrons within the wire [11]. This can be seen in Figure 2 below.

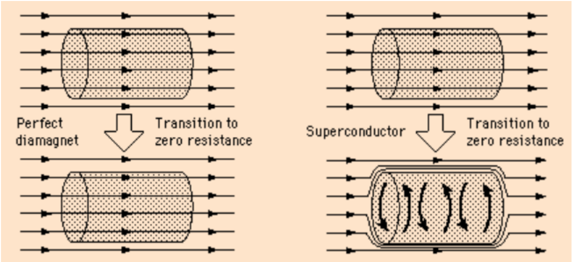

FIGURE 2 [11]
Meissner Effect through non-superconductive and superconductive coils

The image diagram shows the result of a perfect magnet with zero resistance in a non-superconductive state and shows that the magnetic field lines pass through out unopposed. The image on the right is a superconductor experiences the Meissner Effect. As the coil becomes superconductive, the internal magnetic fields are excluded to the outside of the coil [11]. With more magnetic field outside the coil, more force can be created. The extent in which the magnetic fields are excluded is dependent on the material of the superconductive coil [11]. Type I and Type II superconductors are defined from their magnetic field exclusion properties. For Type I superconductors, the internal magnetic field is entirely excluded and for Type II superconductors, the exclusion is defined as a state of mixed magnetic field.

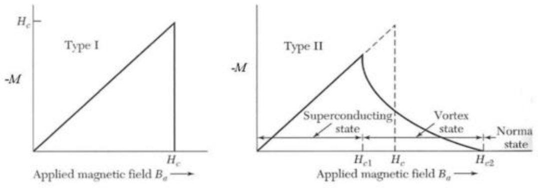

FIGURE 3 [12]
Difference in critical magnetic fields of Type I and Type II figures

Both Type I and Type II reach a state of critical field (H_c) in a linear fashion; however, once this critical state has been reached, there is a distinct difference in phenomena that occurs. Once the Type I conductor reaches the magnitude related to the critical field, it immediately drops out of a superconductive state which limits the effect the coil has on creating forces [12]. In Type II superconductors, after reaching a critical field, vortices begin to form within the coil, causing the “superconducting order parameter [to] drop [...] to zero” [12]. In the rest of the material where the vortices are not found, the material remains superconductive. Also, for Type II superconductors, the H_c value is typically much larger than for Type I. Both the higher H_c and partial superconductive make Type II coils a much more viable option for maglev trains [12]. The SCMAGLEV capitalizes on the Lorentz forces and the Meissner Effect to achieve stable, consistent, fast travel. Factors such as the material of the coil, the shape of coil, and the arrangement of coils affect how much force is created and how it acts upon the vehicle.

SCMAGLEV

Marketed as the train of tomorrow, the SCMAGLEV is developed by the Central Japan Railway Company (JR Central). It is currently only being used on the planned Chuo Shinkansen project to link Tokyo to Nagagoya. The full track should be completed by 2027, and by 2045, the track will also include Osaka [13].

Despite not being fully completed, the SCMAGLEV as an operational track of 42.8 km which as seen 30,000 passengers since 2014 [3]. In order to set the record speed of 603 km/h [13], the SCMAGLEV uses cutting edge superconductive maglev technology.

ELECTRODYNAMIC SUSPENSION

As previously noted in the forces section, the cross product yields a force to levitate the train. Applying a force to the train is not stable enough for safe travel unless a state of equilibrium is reached. A stable equilibrium is reached through electrodynamic suspension (EDS) system [14]. Specifically, EDS magnets on the guideway are induced with current and create their own magnetic fields which interact with the levitation magnetic field lines. The magnetic force created from the EDS system on the side of the guideway interacts with the magnet of the train to achieve stability, as seen in Figure 4 [14].

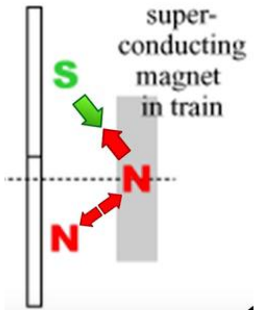

FIGURE 4 [15]
Forces between the train and the EDS system

As the train moves down the track, the magnets on the guideway experience a changing magnetic field due to AC (Alternating Current) current. A separate current is then induced to the top part of the guideway magnet and the bottom part of the magnet [16]. The bottom part of similar poles, opposes the magnet in the train creating a repulsive force on the train, seen via the repulsive arrows at the bottom of Figure 4. While the top part of the magnet of opposite poles creates a force of repulsion on the train. Due to the duality of a repulsive force directed to the right and up and an attractive force directed to the left and up, the summation of these forces cancels their components in the horizontal direction, yielding only an upward force. This upward force yields enough force to levitate the track about 100 millimeters off the ground [17].

For the train to be socially sustainable, the public must feel safe while traveling and without an EDS system, the train would experience a horizontal force which would lead to instability along the path the train travels. The EDS system provides the safety measures to ensure stable, safe, and sustainable travel.

TYPE AND MATERIAL OF WIRE

The superconducting magnets that generate the forces that levitate and propel the train are generated by electrical current, which is carried by superconducting wire. Thus, the material of wire that make up these coils, responsible for the behavior of forces on the train, is of great importance. The SCMAGLEV train uses a supercoil niobium-titanium alloy for its superconductive coils because the alloy has withstood the test of time as the go to material for superconductors. When T.G. Berlincourt and R.R. Hake discovered the superconductive properties of niobium-titanium in 1962, the alloy was described as the "workhorse of superconductors" because their material properties which allowed workability [18]. Now, almost 60 years later, the alloy is still being used on one of the advanced applications of superconductors. Conventional 12-gauge copper wire, generally used in wiring homes, can carry up to 20 amperes of current because of resistivity and excess heat creation, whereas supercool Niobium alloys can carry up to 50,000 amperes [19]. Niobium is an increase of 714,185.714% in ability to carry current compared to copper wire.

Niobium-Titanium is a Type II coil; therefore, it has a high critical magnetic field of 15 tesla. For reference, the magnetic field of the Earth ranges from 25 to 65 microTeslas. Even though other materials, such as Niobium-Tin has similar values for the previously specified properties, Niobium-Titanium is preferred in industry for its mechanical properties [20].

Niobium-Titanium wire is created by embedding a series of fine filaments into a copper matrix for stability [20]. Each filament is finer than human hair at approximately 20 micrometers thick and is beneficial because current flows through the surface of the superconductor, and as the volume of the filament decreases, the total surface area increases. A cross section of the wire can be seen below.

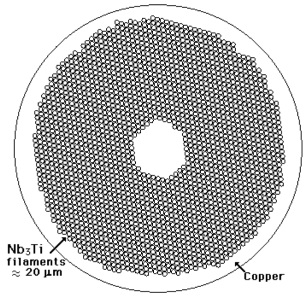

FIGURE 5 [20]
Cross-sectional diagram of Niobium-Titanium filaments enclosed in a copper casing

The overall diameter of the wire is about .7 mm and contains 2100 filaments of Niobium-Titanium alloy [20]. Compared to the conductivity of the Niobium-Titanium alloy, the copper matrix acts as an insulator in the wire. The wire has such a small cross-sectional area due to the proportional relationship between resistivity and cross-sectional area. Even though the wire should maintain a state of superconductivity, if the critical magnetic field is reached, vortices which add resistance to the wire can appear; therefore, the smaller the cross-sectional area, the decrease the effect vortices have on the material.

SHAPE OF COILS

As noted in forces and in the previous section, EDS and the magnetic forces that are generated by superconductive coils are dependent on their orientation, and so the shape of the coils can greatly impact the Lorentz forces which are produced. The levitation/guidance (LG) coils embedded in the U-shaped track are commonly known as "figure-8 coils," due to their resemblance to the number 8 (See Figure 6).

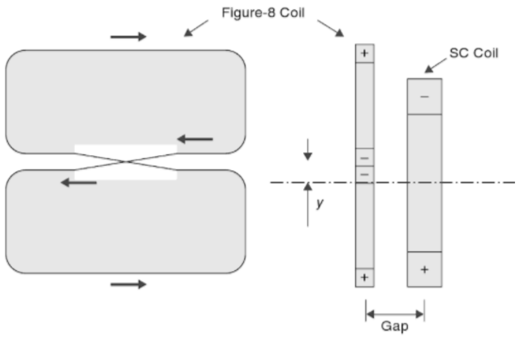

FIGURE 6 [21]
Shape of a "figure-8" coil, as well as the direction of current and space between LG and SC coils

The figure-8 coils are extremely necessary to the operation of the SCMAGLEV, as they are what provides stability to the vehicle's vertical motion. If the train dips below the midpoint, the induced currents in the figure-8 coils create a repelling force from the bottom half of the loop [21]. Likewise, if the train rises above the midpoint, the induced currents would cause forces in the top of the loop to balance out. Without these coils, a stable equilibrium height of levitation is unobtainable, leaving the train useless.

The superconductive (SC) coils are racetrack shaped, and its winding can be divided into two straight horizontal components and two semicircle components.

Levitation forces of the vehicle are generated by electromagnetic interactions between the straight horizontal components of SC coils and those of LG coils [22].

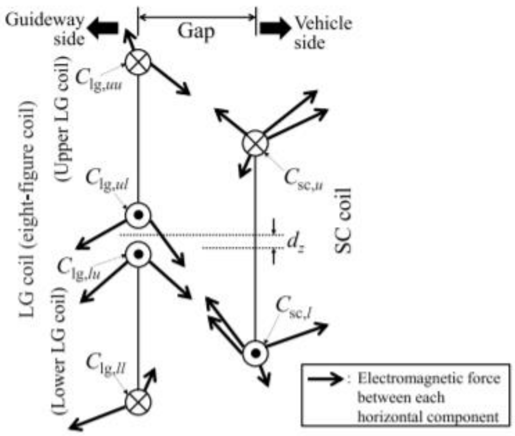

FIGURE 7 [22]
Direction of electromagnetic forces on LG and SC coils

Figure 7 shows the direction of electromagnetic forces between these components. $C_{lg,uu}$, $C_{lg,ul}$, $C_{lg,lu}$, and $C_{lg,ll}$ represent the horizontal components of the LG coil, and $C_{sc,u}$ and $C_{sc,l}$ represent those of the SC coils. Notice that the forces between $C_{lg,uu}$ and $C_{sc,l}$, and those between $C_{lg,ll}$ and $C_{sc,u}$ are smaller in magnitude than the others because of the farther distance these or these portions of the coils. This graphic shows that lateral tensile forces from the guideway act on the upper portion of the LG coil and lateral compressive forces to the guideway act on the lower portion [22].

Forces in the vertical position of the SC coil is dependent on d_z, the balanced displacement, and the horizontal position is dependent on the gap distance between the LG and SC coils.

LINEAR SYNCHRONOUS MOTOR

The SCMAGLEV utilizes a linear motor to propel itself forward. A traditional AC induction motor involves a rotating core constructed from coils of magnetic wire, called a rotor, inside a stationary, magnetic outer casing, called a stator. The magnetic components of the stator create an electric field which induces an electric current within the stator, causing it to spin.

A linear motor is essentially an AC induction motor which has been "rolled out." In such motors, the rotor becomes a flat platform and the stator becomes a track of charged coils.

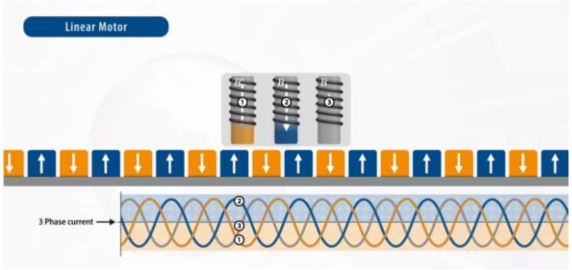

FIGURE 8 [23]
A simple linear motor with a visualization of a 3-phase current

Most often, the stator operates in three phases of electric current as seen above. As one phase of current decrease, another increases to continually supply enough propulsion and attraction between the coils of the rotor platform and the base. Now, the motion of the rotor is linear as opposed to continually spinning. The direction of current, which can be controlled, determines the directions of the forces that move the platform.

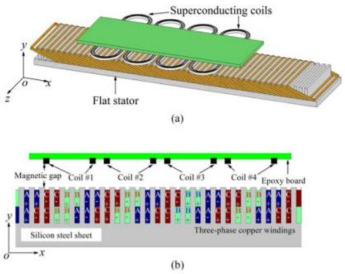

FIGURE 9 [24]
A representation of SC coils on a platform in relation to a flat stator

In Figure 9 above, in part (a), the basic layout of a traditional linear motor is shown. In part (b), different-colored rectangles are used to show the arrangement of copper windings that produce three phases of current. As described in the Forces section and as demonstrated in the equation **F**=q**v** x **B**, the force that acts on the platform will be perpendicular to the electric field, so though the field is in the y direction, the platform will be forced in the x or -x direction.

ARRANGEMENT OF COILS

The arrangement of coils in the SCMAGLEV is critical, as they levitate the train, stabilize the vessel, and determine the direction in which the train will ultimately move. The SCMAGLEV uses a linear motor, but not necessarily in the traditional sense.

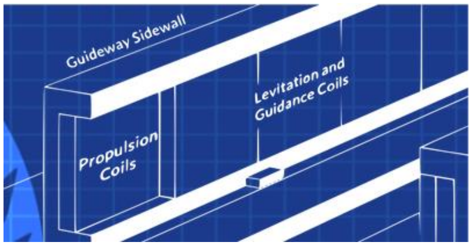

FIGURE 10 [13]
Location of LG and propulsion coils in guideway sidewall

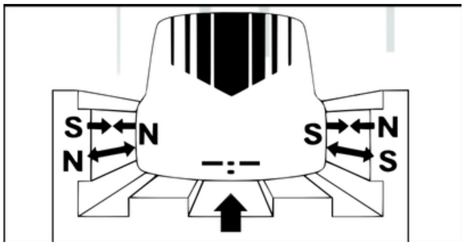

FIGURE 11 [13]
Attraction and repulsion of polarized magnets in the wall

The figure-8 levitation and guidance coils that act as the stator reside embedded in a U-shaped concrete track as shown in Figures 10 and 11. Corresponding coils are also placed in the sides of the train body, acting as the rotor, or platform described in the section above. Despite the vertical orientation of the linear motor, the forces generated are still perpendicular to the orientation of the coils and their respective electric fields, and the train is still propelled forward or backward.

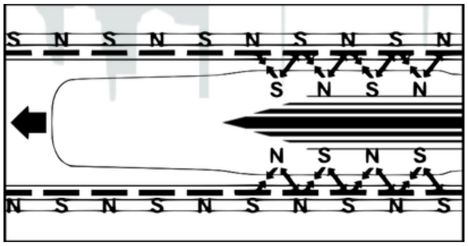

FIGURE 12 [13]
Pattern of alternating N and S magnets in relation to train body

In Figure 12, the repeating pattern of the combination of attraction and repulsion of N and S magnets to propel the train is clearly demonstrated.

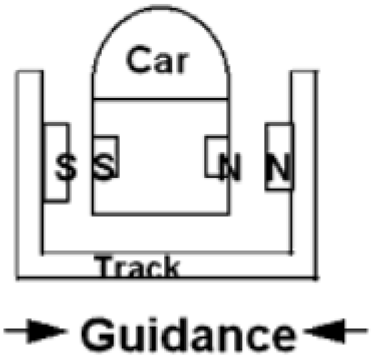

FIGURE 13 [24]
Visualization of similar repelling magnets to keep the train centered on the track

Figure 13 demonstrates how the train is stabilized on the track. N and N and S and S magnets repel each other to keep the train steady in the center.

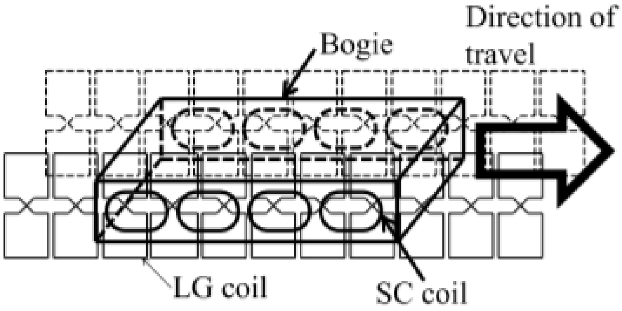

FIGURE 14 [22]
Detailed look at figure-8 LG coils, racetrack shaped SC coils, and direction of movement

Figure 14 shows the arrangement of the LG and SC coils mentioned in the previous section as well as indicating the direction of travel caused by their interactions.

Because the train is a levitating device, there is a gap between the coils of the train and those in the walls of the track. This gap is the same on both sides of the train and is shown in Figures 6 and 13.

LIMITATIONS

As stated before, it is critical that a superconductor stay at a low enough temperature to operate because if the temperature drops too low, not enough force will be created, and the layer formed by levitation between the train and the wire will disappear. If this is the case, the train will derail from the track while traveling at speeds of over 600 km/hr resulting in a catastrophic and deadly crash.

For SCMAGLEV be socially sustainable, a consistent method of coiling is needed to guarantee the safety of all passengers.

According to Kazuo Sawada, deputy director general of the Maglev System Development Division at the Central Japan Railway Company, the developer of SCMAGLEV, the future of superconducting maglev trains may lie in high-temperature superconducting (HTS) wire [25]. A high temperature superconductor can achieve superconductivity at temperatures up to approximately 61 degrees Celsius higher than those of its low-temperature superconducting counterparts. Wireless power transfer (WPT) technology would allow constant current to reach the HTS receiver (Rx) coils and multi-copper antenna (Tx) coils that make up the system.

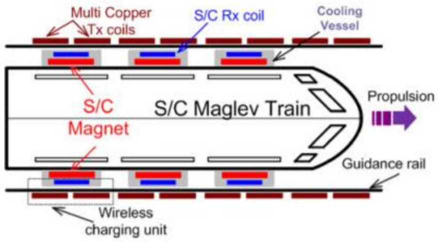

FIGURE 15 [26]
Location of Tx and Rx coils

As seen in Figure 15, tubes of liquid nitrogen would be pumped along the sides of the coils to keep them at a low enough temperature to allow for superconductivity to occur. Also seen is the wireless charging unit and the placement of Rx and Tx coils in relation to one another. In an experiment by Yoon Do Chung, Chang Young Lee, Dae Wook Kim, Hyoungku Kang, Young Gun Park, and Yong Soo Yoon, all from respectable institutions in South Korea**,** "effects of transmission efficiency between moving Rx coil and multi-Tx array with different wire of Rx" were examined [26]. To minimize the number of variables that could affect the results, all coils of Tx and Rx were wound by helix type, the Tx coil was composed only of cable type copper wire, and the Rx coils used copper cable, solid, litz, and HTS wire [26].

"The cooling cost of superconducting wires is caused by AC loss, which is the sum of magnetization losses and transport current losses during AC charging" [27]. Also, "The LC resonance of Tx and Rx coils constitute a source resonance circuit to generate an alternative non- radiative magnetic field in the resonance coupling coils" [27]. What this means is, when the oscillation of the source resonance circuit is in sync with the receiver circuit, the resonant flow of flow of charge, or current, is maximized. Maximizing current minimizes thermal loss, and thus transfer efficiency is maximized. Like the SCMAGLEV, liquid gas (in this case nitrogen) is used to keep these wires cool.

It was found that cooled copper Rx coils reflected power rates 5% higher than their non-cooled counterparts. Current distribution over the HTS Rx coils was over 1.5 times higher than other cooled materials, while voltage distribution was lower, meaning lower responsiveness and higher stability [26]. In terms of energy transfer efficiency, the HTS coils were over 20% more effective than the other wire coils while consuming less liquid nitrogen (LN2). It is worth noting that the HTS coils are about three times smaller than the solid, copper cable, or litz coils [26].

It is important to always keep in mind the efficiency of the system you are building. As HTS coils can reach superconductivity at higher temperatures, less LN2 is needed to cool it to its ideal temperature. This provides a possibility for the future.

LOCATING PROBLEMS

On the surface level, propelling a train to such high speeds and lowering commute appears to be a clear choice for the future of transit; however, the technology has various limitations in implementation. One of the biggest limitations to maglev technology is the need to locate potential problems in the coils.

Superconducting coils have limitations and are subject to abnormalities. Because this could lead to potential disaster, such as a derailed train, devices can be used to locate these points of error so an engineer may fix them. "When a defect occurs in the propulsion coils and/or cable joints, a partial discharge (PD), which is a symptom of insulation degradation, may occur in them" [28]. Masatake Kawada of the Institute of Technology and Science at the University of Tokushima in Japan, along with members of the Yamanashi Maglev Test Center, Research & Development Promotion Division, Maglev Systems Technology Division, performed a study in which four half-dipole antennas of a radio interferometer system were mounted on a replica of a maglev vehicle [28]. A smoothed coherence transform (SCOT) was used to suppress unrelated signals and enhance related signals that the antennas picked up.

The system measures the change in waveforms of electromagnetic waves as the position of the antennas move in the x-direction from -0.5m to +0.5m. The amplitudes of these waveforms are compared, and from the comparison a rough location of the PD source can be determined [28].

COST

While promising, the application of superconductivity to levitate a train is currently quite costly. According to predictions from SCMAGLEV and the Central Japan Railway Company, the financial requirement of constructing an operating SCMAGLEV train is a $43 million per mile commitment [29]. The superconductive coils are cooled through the use of liquid helium, which costs approximately \$0.50 per evaporated liter. While the cost per coil may not necessarily seem expensive, when constantly applied to a track of 215 miles or greater, the expense increases drastically [30]. Beyond that, the materials required for the project are expensive. Because of their ability to reach Type II superconductive properties, rare earth metals are often used in the manufacturing of these coils, and rare earth metals are significantly more expensive than other metals. The superconductive coils in the SCMAGLEV are constructed from a niobium-titanium alloy, and pure niobium metal cost is about 18 dollars per 100 grams [31]. To put that in perspective with a more commonly known metal, aluminum costs only about 20 cents per 100 grams [32].

EXPANSION AND THE FUTURE

Currently, SCMAGLEV technology is only being used by JR Central. However, the benefits of this technology are making their way into practice. Under the promotion of JR Central, The Northeast Maglev Project is developing an SCMAGLEV track to connect Washington DC to New York City, linking in Baltimore and Philadelphia along the way [33]. It is expected that populations in the Baltimore-Washington region will rise from 8.1 million people to 9.7 million people by 2040. Employment in those metropolitan regions is expected to grow from 4.7 million to 5.9 million jobs in the same time frame [34]. With growing populations, need to commute to jobs, and even growing tourism in the region, a need for a socially sustainable method of transportation is needed. SGMAGLEV can be that method.

Superconductive maglev transportation technology is joining electric cars and biofuel-powered airplanes as environmentally friendly transport options. The SCMAGLEV consumes only 50% energy and emits only a third of the carbon dioxide emissions of a commercial airline [32]. However, common problems amongst new-wave eco-friendly options remains the same. The costs of environmentally sustainable options are more expensive than those of their heavily polluting counterparts, and there may be struggles with hidden environmental effects. The SCMAGLEV train does not directly pollute the environment with harmful gases, such as carbon dioxide, however, the manufacture of liquid gases to cool the coils consumes great amounts of energy, which was most likely produced by the burning of fossil fuels which do produce harmful gases.

To build superconductive coils, rare-earth metals which are limited resources, are required. Those metals used could be used for other environmentally sustainable technologies such as solar panels.

One of the Grand Challenges set forth by the National Academy of Engineers is to "Restore and Improve Urban Infrastructure." This includes "engineering integrated transportation systems, making individual vehicle travel, mass transit, bicycling, and walking all as easy and efficient as possible" [35]. SCMAGLEV systems that can safely travel at speeds of 603 km/hr could potentially link cities in ways unseen. Workers from Pittsburgh could commute to a job in Philadelphia in less than an hour. Products and foodstuffs could be delivered in a fraction of their current times.

SCMAGLEV is also serving as an inspiration for further innovation. Despite the final track not being finished yet, superconductive magnetic levitation is already inspiring yet another new wave of transportation. The Hyperloop is a conceptual follow-up to SCMAGLEV, using superconductive maglev coils and a train pod in a depressurized tube to launch people to their destinations at even faster speeds. Prominent engineer and businessman Elon Musk, with his company SpaceX, and the company Hyperloop-One is promoting and developing this technology.

ON THE RIGHT TRACK?

Superconductive levitating vehicles were first officially proposed by Dr. J. R. Powell and Dr. G. R. Danby with the intention of creating a better, faster, safer train to fill the constant need of transportation. Since its conception in 1963, the idea of using superconductivity to levitate and propel a vehicle has grown into one of the most intriguing technologies for the future.

It is evident that in its current state, the SCMAGLEV is in no way economically sustainable. In the social sphere, the SGMAGLEV can connect passengers and workers to places unavailable to them before, improving the infrastructure of the country. Environmentally, the obtainment of rare earth metals and liquid helium and the construction of the track would initially alter the ecosystems in the way. However, over time, should these tracks replace buses, cars, or other fossil-fuel powered vehicles, superconductors in the SCMAGLEV provide a sustainable future.

For many, the massive financial investment involved in an SGMAGLEV project is a major deterrent and outweighs its long-term environmental impact. For others, the opportunities associated with the connection to booming metropolises and the long-term kindness to the environment is worth the investment. Although not yet fully perfected, SCMAGLEV has shown that it is an option for a sustainable future.

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