Research and Development Concerning Superconducting Maglev and Research on Applying Superconducting Maglev Technology to the Conventional Railway System

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RTRI is advancing the fundamental research and development concerning superconducting maglev. The topics of this issue are characteristics of maglev vehicle dynamics, experimental production and evaluation of REBCO high-temperature superconducting coils. RTRI is also promoting the applied research based on maglev technology to the conventional railway system. The topics of this issue are the LIM-type eddy-current rail brakes and the flywheel energy storage system.

**Keywords:** levitation railway, superconducting linear, conventional railway, superconducting magnet, ground coil

1. Introduction

The groundbreaking idea of levitating and guiding vehicles using onboard superconducting magnets, the basic principles for the current superconducting magnetically levitated transportation system, was originally proposed by Dr. J. R. Powell and Dr. G. R. Danby of Brookhaven National Laboratory in the U.S. This idea was officially jointly presented by Dr. Powell and Dr. Danby in 1966 at a gathering of the American Society of Mechanical Engineers, in their presentation “High-Speed Transport by Magnetically Suspended Trains” [1]. The year 2016 is therefore a special year because it marks the 50th anniversary of this announcement. This paper discusses the original proposal by Dr. Powell and Dr. Danby, recent developments and the current status of maglev train development with a view to using the technology in practice. This paper also presents RTRI’s basic research on maglev technology and its work aimed at applying these technologies to conventional railways.

2. Developments in levitation railway technology

2.1 50 years since “superconducting magnetic levitation” was first proposed

In March 2016, to commemorate the 50th anniversary of the original “superconducting magnetic levitation” proposal mentioned above, Dr. Powell’s son gave a speech entitled “Powell and Danby’s Grand Idea: 50 Years of Maglev History” at the Brookhaven National Laboratory [2], [3].

In this speech, it was revealed that Dr. Powell had made a proposal earlier in 1963 for a superconductivity-based transportation system. The proposed system, however, was too costly to be practical as superconductors were arranged on the track.

Later in 1966, Dr. Powell together with Dr. Danby proposed a more practical superconducting magnetic levitation system built on the following three basic concepts, also shown in Fig. 1: (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 (EDS = Electro Dynamic Suspension System); and (3) null flux (zero linkage between superconducting coils on the vehicle and short circuit coils on the track with guidance coils vertically installed relative to the ground surface as shown in Fig. 1) used for vehicle guidance. Subsequently in 1971, it is said that Dr. Powell “formally” announced the combination of a superconducting levitation system and a LSM (Linear Synchronous Motor).

In Fig. 1, the vehicle is levitated and guided by the electromagnetic force generated between the coils on the ground and the superconducting coils (magnets) on the vehicle, in addition, the electromagnetic force is proportional to the product of the magnetomotive force of the ground coils multiplied by that of the onboard coils.

As ground coils, which outnumber onboard coils, need to be arranged continuously along the track, it is more cost effective for the entire system to use a smaller magnetomotive force in ground coils and a greater magnetomotive force in onboard coils. As superconducting coils have no electrical resistance, their magnetomotive force can be increased (indicated as a larger cross section in Fig. 1) without electric energy loss due to Joule heating whilst providing a higher lift (15 cm or more) above the ground.

The above features are described in their paper as follows: electric energy loss can be minimized by putting a current of several hundred kA through onboard superconducting coils, which generates no loss, and limits the current through the ground coils to several kA, while costs...
2.2 Practical applications of transport system using linear motor technology

A number of transport systems using linear motor technology have been placed into service in cities over the past few years. In December 2015, the City of Sendai started a linear metro system on the subway Tozai Line that uses the LIM (Linear Induction Motor) technology to drive the metal wheels.

The Tozai Line is the seventh linear metro system line to have opened in Japan. In February 2016 in Korea, the long-delayed Incheon Airport Maglev Line finally opened [4]. In May 2016 in the City of Changsha, China, the Changsha Maglev Express started trial commercial operations [5]. The systems in Korea and China are both

| Country | Name (Location) | Year of launch | Distance (km) | Propulsion/suspension methods |
|---------|-----------------|----------------|---------------|------------------------------|
| Canada  | Vancouver SkyTrain | 1985           | 68.6          | LIM/Metal wheel               |
| Canada  | Toronto Subway Scarborough Line | 1985 | 6.4 | LIM/Metal wheel |
| U.S.    | Detroit People Mover | 1987           | 4.73          | LIM/Metal wheel               |
| Japan   | Nagahori Tsurumi-ryokuchi Line (Osaka) | 1990 | 15 | LIM/Metal wheel |
| Japan   | Oedo Line (Tokyo) | 1991           | 40.7          | LIM/Metal wheel               |
| Malaysia| Rapid KL Kelana Jaya Line (Kuala Lumpur) | 1998 | 29 | LIM/Metal wheel |
| Japan   | Kaigan Line (Kobe) | 2001           | 7.9           | LIM/Metal wheel               |
| China   | Shanghai Transrapid | 2002           | 30.5          | LSM/EMS                       |
| U.S.    | AirTrain JFK (New York) | 2003 | 13 | LIM/Metal wheel |
| China   | Guangzhou Subway Line 4 | 2005 | 43.6 | LIM/Metal wheel |
| Japan   | Nanakuma Line (Fukuoka) | 2005 | 12 | LIM/Metal wheel |
| Japan   | Linimo (Nagoya -Toyota) | 2005 | 8.9 | LIM/EMS |
| Japan   | Imazatosuji Line (Osaka) | 2006 | 11.9 | LIM/Metal wheel |
| China   | Beijing Subway Airport Express | 2008 | 28.1 | LIM/Metal wheel |
| Japan   | Green Line (Yokohama) | 2008           | 13.1          | LIM/Metal wheel               |
| China   | Guangzhou Subway Line 5 | 2009 | 31.9 | LIM/Metal wheel |
| Korea   | EverLine (Yongin) | 2013           | 18.49         | LIM/Metal wheel               |
| China   | Guangzhou Subway Line 6 | 2013 | 24.3 | LIM/Metal wheel |
| Japan   | Tozai Line (Sendai) | 2015           | 13.9          | LIM/Metal wheel               |
| Korea   | Incheon Airport Maglev Line | 2016 | 5.6 | LIM/EMS |
| China   | Changsha Maglev Express | 2016          | 18.55         | LIM/EMS |

and the required cooling capacity can be minimized as superconducting coils need to be installed only on the vehicle.

In 1966 when superconducting coils were still not generally known in the world, the proposal could only be realized by Dr. Powell and Dr. Danby, both physicists at the Brookhaven National Laboratory and specialized in the study of particle accelerator and nuclear fusion and well versed in superconductive technology.

As the proposal gave impetus to the start in Japan of the development of a superconducting magnetically levitated transportation system, in April 1997 RTRI held Special International Lecture and invited Dr. Powell who delivered a speech entitled "The Development of a Superconducting Magnetically Levitated Transportation System" at the launch of running tests on the Yamanashi maglev test line.
ordinary conducting levitation railways, combining EMS (Electro Magnetic Suspension System) and LIM propulsion – they do not use superconductivity.

A list of transport system using linear motor technology currently in commercial operation is given in Table 1, which shows that transport system using linear motor is in operation on 21 lines in six countries, totaling 446 km. Figure 2 shows the total distance of commercial operations per country. China, Japan and Canada have the largest lengths of line in operation. Looking at the types of method used, 16 lines totaling 383 km use a combination of metal wheel suspension and LIM propulsion and three lines totaling 33 km use a combination of EMS and LIM propulsion, in what are known as normal conducting levitation railway with a medium-to-low speed of around 100 km/h. Up until the end of FY2015, only one example of this was in operation, namely, “Linimo” in Japan. In 2016, the method was adopted on commercial lines in Korea and China. Currently, construction of lines using this technology is underway in Beijing with a planned entry into service in the near future.

At the moment, there is only one line located in Shanghai and totaling 30 km that uses a combination of EMS and LSM propulsion for high-speed normal conducting levitation railway (transrapid) with a top speed of 430 km/h.

The superconducting magnetically levitated transportation system currently being developed in Japan using a combination of EDS and LSM propulsion, which will have a top speed of around 500 km/h, will be the first commercial operation of this kind in the world. Current plans are to launch commercial operations in 2027 between Tokyo and Nagoya (286 km) followed later by an extension to Osaka [6].

![Fig. 2 Total length of transport systems using linear motor technology in commercial operation by country](image)

### 2.3 Hyperloop

In May 2016, the first public test of Hyperloop, a next-generation transportation system, was carried out in the desert of Nevada, the U.S., drawing keen attention from the public [7]. The proposal for this system was made in August 2013 by Elon Musk, CEO of SpaceX and Tesla Motors. The test itself, carried out using maglev trains and achieving a maximum speed of just 186 km/h, did not show anything new. However, the project has been generating great expectations as it touches upon many innovative ideas, namely: a vacuum tube to reduce running resistance to help achieve a near-sound, maximum speed of 1200 km/h; solar power generated on the track to provide power needed for propulsion; an extremely low-cost transportation system developed within a short time frame; ideas submitted from outside on a competition basis, and the fact that the concept for the system is being proposed by a famous figure. A number of areas have been rumored to be candidate to host sections of the system, including Los Angeles – San Francisco, Dubai – Abu Dhabi and Helsinki – Stockholm. In a related move, Ulsan National Institute of Science and Technology (UNIST) of Korea announced in July 2016 that it would start development of Hyperloop-related technologies.

A number of companies have been involved in the development of the Hyperloop including Hyperloop One, which staged the public Hyperloop tests, and Hyperloop Transportation Technologies. A number of carbody supporting systems are said to be in the running for selection, including air cushioning and Inductrack based on a Halbach array of permanent magnets (a special arrangement of permanent magnets to strengthen the magnetic field that is generated). While presentations about the Hyperloop were made at the WCRR, Maglev 2016 and other international meetings, no specifics have been disclosed. Amid many uncertainties, the project at the moment appears to be looking at technical details.

The project also appears to be looking not just at passenger transport but cargo transport as well. That may be because there is a justifiable level of demand for ultra-high-speed transport of cargo. While it is not certain whether these moves could help facilitate Hyperloop’s early entry into service, the project deserves continued attention as its impact is expected to be huge when it succeeds commercially.

### 3. Related R&D at RTRI

#### 3.1 Basic research on levitation railway

RTRI has been advancing basic research on maglev under the Master Plan for Superconductive Maglev Technological Development approved by the Minister of Land, Infrastructure, Transport and Tourism. As FY2016 is the final year of the RTRI master plan, the institute has been collating the results achieved thus far.

The previously-mentioned basic concepts that Dr. Powell and Dr. Danby envisioned for a superconducting magnetically levitated transportation system can be roughly translated as follows: performance enhancement of onboard superconducting magnets and simplification of ground coils hold the key to achieving overall cost reduction for a linear system. This approach can also be applied to the vacuum tube system mentioned earlier in this paper.

As part of its effort to further cultivate the above approach with new technologies and ideas, RTRI has been developing high temperature superconducting coils in the area of superconducting magnets and a PLG (Combined...
Propulsion, Levitation and Guidance System) coil, which plays a part in all three aspects, propulsion, levitation and guidance, in the area of the ground coil [8].

The PLG coil development project has been completed successfully. The coil offers simplification of configuration including reduction in the required number of coils, achieving substantial reduction in construction cost, compared with the conventional system which uses two separate coils, one for propulsion and the other for levitation and guidance. As shown in Fig. 3, the PLG coil was tested for verification of workability using a full-size guideway model, which showed that the PLG coil can be installed without any substantial modification of the current guideway.

The development of a high-temperature superconducting coil started with the basics, i.e. evaluation of rare-earth high-temperature superconducting wire, as the coil appeared to offer many benefits. For example, as the coil can be cooled at a higher temperature, vacuum insulation casing around the coil can be reduced in size and weight. That, in turn, means that the superconducting coil can be positioned closer to the ground coil, which in effect increases the magnetomotive force of the superconducting coil. Furthermore, refrigerant, such as liquid helium, are no longer needed while the on-board refrigerator consumes less electricity. Following a substantial investment in time and effort spent on development, RTRI recently succeeded in exciting a full-size high-temperature superconducting coil, which is shown in Fig. 4. This development is discussed in full in the article entitled “Development of a Real-scale REBCO Coil for the Demonstration of a Magnetomotive Force of 700 kA” in the January 2017 issue of RTRI REPORT (the English version is described in this issue of Quarterly Report, pp.318 - 323). Going forward, vibration tests simulating running vibration will be conducted to verify that the coil remains sufficiently cool and excited, even when being shaken.

The article “Effects of Electrical Gap Reduction on the Design of Ground Coils and Superconducting Magnets” in the January 2017 issue of RTRI REPORT discusses the results of the following two scenarios which are based on the hypothesis that the electrical gap between the superconducting coil and the ground coil can be reduced with the introduction of the high-temperature superconducting coil mentioned above.

(1) Without any change made to the specifications of ground coils and superconducting magnets, augmentation of flux (linkage) is used to improve the characteristics of electromagnetic force.

(2) The magnetomotive force of superconducting magnets is reduced without any change to ground coil specifications and while keeping electromagnetic force characteristics at or above the current level.

Currently, numerical simulations are also being conducted to evaluate how the benefits of introducing high-temperature superconducting coils can be optimized.

### 3.2 Study on application levitation technology to conventional railways

The January 2017 issue of the RTRI REPORT presents unique technologies such as LIM-type eddy-current rail brakes, superconducting flywheel energy storage systems, magnetic heat pumps and evaluation systems for magnetic fields inside railway vehicles in a study on applying levitation railway-related technologies to conventional railways.

The article “Verification of the Reliability of a Superconducting Flywheel Energy Storage System and Its Application to the Railway System” in the January issue (the English version is described in this issue of Quarterly Report, pp.305 - 310) discusses performance verification of a flywheel energy storage system test unit installed at a mega-solar power plant in Komekurayama, Yamanashi Prefecture. The verification test confirmed that, while the target storage volume of energy could not be achieved due to vibration of the flywheel shaft, the test unit was able to stabilize output fluctuations in photovoltaic power generation.

Verification tests also found that the high-temperature superconducting magnetic bearing including the high-temperature superconducting coils shown in Fig. 5 demonstrated the expected performance. That is, performance in terms of cooling, levitation and rotation of the flywheel rotor at high speed as designed, without altering the flywheel characteristics. No issues were found when the flywheel was levitated and put through repeated excitation/demagnetization and heating/cooling sessions for a total of more than 3000 hours. After these lengthy tests, the high temperature superconducting coils were disassembled for performance comparison before and after the test. No deterioration in performance was found.

The coil is made of rare-earth high-temperature superconducting wire which has the same specifications as high temperature superconducting coil for levitation railways, discussed in the previous section of this paper. While different in shape, those coils are the same in that they are both continuously subjected to significant load and vibration. It is hoped that further progress in R&D on these coils will lead to new state-of-the-art technologies.
As an offshoot of RTRI’s research and development into superconductivity-related technology, efforts have also been made to develop superconducting cable systems for other railway applications [9].

4. Conclusion

On the 50th anniversary of the original proposal for superconducting magnetic levitation, this paper looks back at the proposal made at that time. While practical application of maglev technology has largely been based on a combination of metal wheel suspension and LIM propulsion, levitation is gradually becoming more popular. Coupled with this, new ideas have appeared, such as the Hyperloop. Bearing all this in mind, the original concept of superconducting magnetic levitation still stands out for its practicality. Since the initial proposal, related achievements have been made thanks to efforts by senior fellows in the field.

RTRI will continue to advance research and development on superconducting magnetic levitation, with a focus on basic research on maglev and application of related technologies to conventional railways. Further effort will be made to seek expertise from within and outside RTRI to pursue these goals efficiently.

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Finally, Dr. G. R. Danby, who co-proposed superconducting magnetic levitation, passed away on August 2, 2016, at the age of 86. We would like to offer our heartfelt condolences and pray that his soul may rest in peace.

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