

Load test of Superconducting Magnetic Bearing for MW-class Flywheel Energy Storage System

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Abstract. A flywheel energy storage system (FESS) stores electrical power as kinetic energy of a rotating flywheel rotor. Since the storage energy of the FESS is proportional to the weight of the rotor and the square of the rotating speed, the heavy weight and high speed rotor leads a FESS to a high power and a high capacity. However a conventional FESS limits in both the rotor weight and the rotating speed because of using mechanical bearings. A superconducting FESS (SFESS) utilizes a superconducting magnetic bearing (SMB) to levitate and rotate the flywheel rotor that has ton class weight and high speed rotation without mechanical contact. As the SFESS with 300 kW demonstrated at Mt. Komekura in Yamanashi prefecture, the SMB in the SFESS levitated the 4-ton rotor. The SMB consisted of a high temperature superconducting magnet (HTS magnet) and a HTS bulk, and utilized a repulsive force between the HTS magnet and the HTS bulk. The demonstration of the SFESS has been carried out successfully at Mt. Komekura. Now the next step development was started to aim a MW-class SFESS. The MW-class SFESS needs the SMB levitated and withstood a 10 ton-class load. This paper describes a design of the 10 ton-class SMB and the result of the load test of the developed SMB

1. Introduction

A FESS stores an electrical power as a kinetic energy in a rotating flywheel rotor and discharges the power by transforming the kinetic energy into electrical power via an electrical motor and generator. The FESS, which is different from a secondary battery that uses a chemical reaction, performs the operation of long lifetime because it has no chemical degradation like the secondary batteries. Particularly, a high temperature superconducting FESS (SFESS) uses a superconducting magnetic bearing to support a high speed and heavy weight rotor without a mechanical contact, in order that the operation of the long lifetime is realized. The Railway Technical Research Institute and Furukawa Electric have developed the SFESS in the NEDO project with Yamanashi prefecture government, Kubotek and Mirapro [1]-[3]. The SFESS that was developed and was demonstrated in the project had a rotor of 4 tons (2 m in diameter) and provided an electrical power of 300 kW.

A superconducting magnetic bearing (SMB) was consisted of a high temperature superconducting magnet (HTS magnet) in the stator side, and a HTS bulk in the rotor side. The both are made from



rare-earth barium copper oxide (REBCO) superconductor. The HTS bulk was levitated by a shielding effect, which was generated with the magnetic field of the HTS magnet. The HTS magnet and the HTS bulk were cooled to cold temperature of several-ten K. The SMB was made of the HTS magnet, the HTS bulk, and a heat insulation chamber, in which the temperature kept at less than 50 K with vacuum and a multi-layer insulation. The 300-kW SFESS that levitated the 4-ton rotor stabilized and averaged output power of the photovoltaic power (PV) plant provided by Public Enterprise Bureau of Yamanashi Prefecture (Yamanashi Prefecture) as figure 1. The Yamanashi Prefecture constructed a one-MW PV plant for the demonstration of the SFESS. The stable electrical power was transmitted to a commercial line of Tokyo Electrical Power Company (TEPCO).

The demonstration system for the field test of the SFESS was consisted of the SFESS, the control system of the network stabilization, and two-way converter. The SFESS charged electric power from the PV plant and discharged the power to stabilize the output power that fluctuated for short period. In the field test, the SFESS was performed to stabilize the output power at the connection point to the electrical power grid of TEPCO. When the output of the PV plant was 500 kW, fluctuation of the power was within ± 100 kW. The output of the PV plant is shown with a orange color line in graph of figure 1. The SFESS charged and discharge electrical power depending on fluctuation of the output of the PV plants as shown with a green color line. The output at the connection point totally became constant and stable by control of the short period fluctuation, as shown with a red color line.

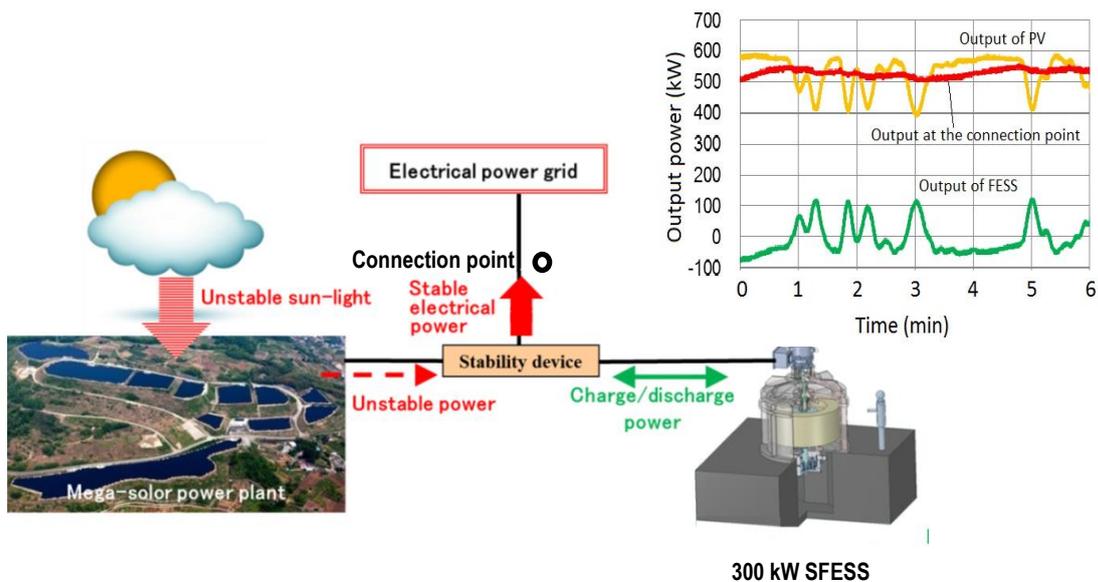


Figure 1. Configuration of the SFESS demonstrated at Mt. Komekura in Yamanashi. The SFESS was charged and discharged by the one-MW PV plant. The graph shows output power of the SFESS, the PV plant, and the connection point to the grid of TEPCO.

2. Configuration of superconducting flywheel energy storage system (SFESS).

Configuration of the SFESS is shown in figure 2. The flywheel rotor of 300-kW SFESS was composed of a carbon fiber glass reinforced plastic (CFRP), which was the world largest volume of 2 m in diameter, 1 m in height, and 4 tons in weight. The motor/generator was a synchronous machine of a commercial permanent magnet type, and was set on top of the FESS. The vacuum seal along the rotor shaft between air and vacuum area in the outer vacuum vessel was applied a magnetic fluid seal. The CFRP rotor and the SMB were in an inner vacuum vessel in which a thin helium gas with 100 Pa was filled. The pressure of the helium gas was chosen to avoid an air friction of the CFRP rotor rotation and to cool the HTS bulk of the SMB. The SMB only supported the radial direction force of the rotor, so the thrust direction force was supported by two active magnetic bearings (AMB) set at

above and below of the rotor shaft. Figure 4 shows an overview of the FESS, and the SMB was located at the bottom of the SFESS. The specifications of the SFESS are shown in Table 1.

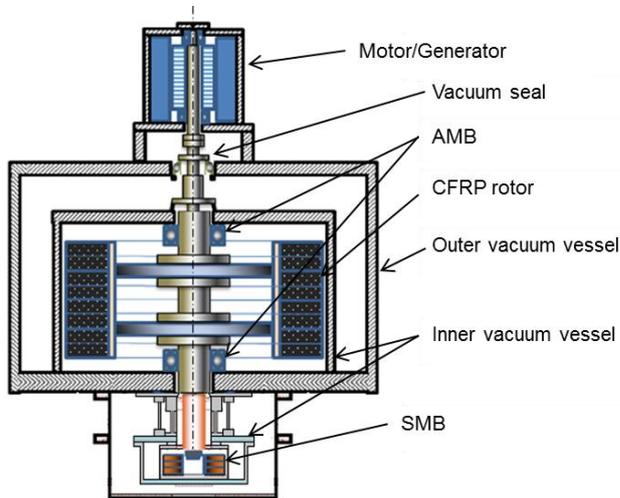


Figure 2. 300-kW HTS flywheel energy storage system (SFESS). The SMB consisted of the HTS magnet and the HTS bulk in the inner vacuum vessel, in which thin He gas filled.

Table 1. Specification of the SFESS.

Item	Specification	Remark
Outer diameter	2,000 mm ϕ	consisting of nine layers with a thickness of 100 m
Inner diameter	1,400 mm ϕ	
Height	900 mm	
Weight	4,000 kg	excluding the rotating rod
Rotor material	CFRP	
Rotating speed	6,000 rpm	rotating speed at the outermost rim: 628 m/s
Storage capacity	100 kWh	

3. Configuration of superconducting magnetic bearing (SMB).

The SMB developed for the levitation of a 4-ton rotor consisted of the HTS magnet and the HTS bulk. The HTS magnet was composed of 5 double pancake coils, which were made of REBCO wires. The REBCO wires were manufactured by Superpower (type SCS6050AP). The HTS bulk was composed of 3 HTS plates, which Nippon Steel & Sumitomo Metal developed by a quench melt growth (QMG) process [4]. The schematic configuration of the SMB is shown in figure 3. The rotor axis included the HTS bulk was levitated by the magnetic field generated by the HTS magnet as the stator. The specifications of the superconducting wires and the HTS magnet are shown in Table 2.

Table 2. Specifications of the HTS wires and the HTS coil.

Item	Specification
Wire	Product of Superpower (type SCS6050AP)
Width of tape	6 mm
Thickness of tape	0.1 mm
Inner diameter of HTS coil	120 mm
Outer diameter of HTS coil	260 mm
Height of the HTS coil	17.6 mm

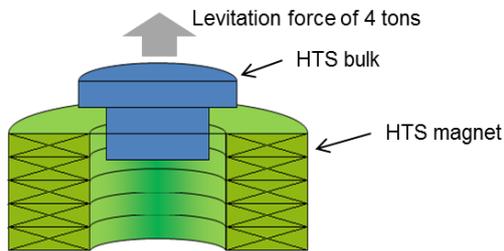


Figure 3. Schematic drawings of the HTS magnet and the HTS bulk in the SMB. The HTS magnet consisted of 5 HTS double pancake coils, and the HTS bulk consisted of 3 HTS plates

4. Test of SMB in SFESS.

The HTS magnet stacked five double pancake coils was cooled by conducting cooling with a GM refrigerator, which had a cooling capacity of 50 kW at 20 K. The HTS bulk was cooled by heat transfer of thin helium gas from cold surface of the HTS magnet.

The SMB was settled in the SFESS prototype (figure 4) and was tested to confirm the levitation properties while supporting the 4-ton rotor. The procedure of the SMB cooling is following; 1) Exhausting air in the vacuum chamber and the inner chamber including the HTS magnets and the HTS bulks for vacuum thermal insulation, 2) Operating the GM refrigerator to cool the magnets, 3) after the coil cooling, introducing helium gas until about 100 Pa to cool the HTS bulks. After cooling to less than 50 K, the levitation height of the rotor was measured under 4-ton load while increasing the magnet operation current. As the result of the current loading test of the SMB, levitation height of the rotor axis is shown in figure 5. The rotor axis was set at 19 mm in height from the original zero position. The 19 mm was height of a touch-down mechanical bearing. The axis was settled on the touch-down bearing with no current load. The rotor was levitated when the coil current exceeded 76 A, and the rotor gained the height by 1 mm per 1 A.



Figure 4. 300-kW SFESS was constructed in a Mirapro factory. The SMB was set on the bottom of SFEE and levitated the FW rotor.

Figure 6 shows the levitation height that depends on the operating coil current in the levitation test. After the magnet engaging, the levitation height was dropping gradually. The coil current was increased with 0.2 A more to keep the constant height of the rotor. We think the height was decreased due to the flux creep in the HTS magnet and the HTS bulk. The long term change of the height is shown in figure 7. The levitation height was changed only in first several hours. Since the magnetic fluxes were finally settled in the superconductors, the SMB provided a stable levitation over 1,000 hours.

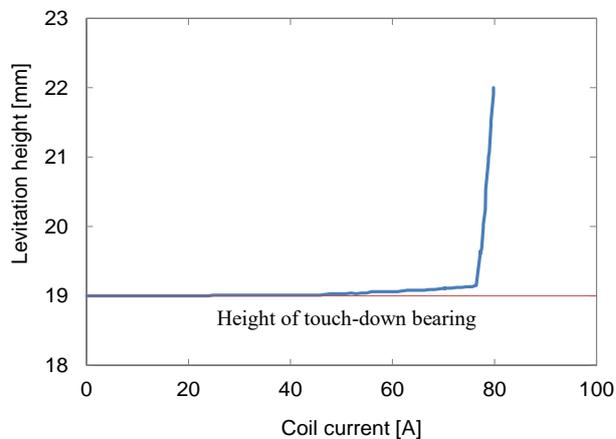


Figure 5. The levitation height of the rotor axis included HTS bulks was measured during the coil current feeding to the SMB magnet. Start height with 19 mm was height of a touch-down bearing, on which the rotor located without the current.

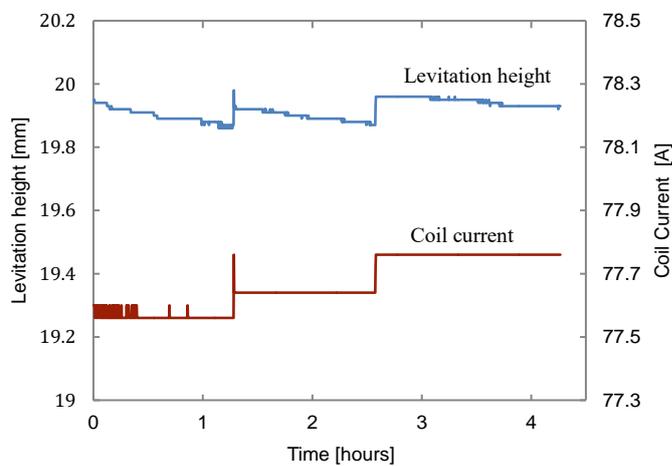


Figure 6. Levitation height depending on time for short time. The coil current increased to keep a constant lever of the height.

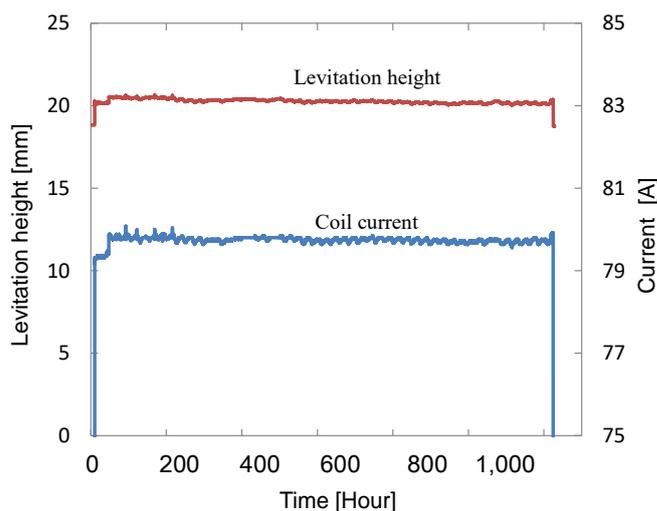


Figure 7. Levitation height depending on time for long time period. After initial adjustment of the current, the current was fixed at a constant value. Fluctuation of the current in the graph was occurred due to temperature changing.

5. Levitation load test of 10 tons in weight.

The capacity target of the SFESS is 1 MW power for stabilization of a network that connects renewable energy sources for short period. The 1 MW class SFESS has the rotor of 10 tons in weight, and the SMB needs levitate force of 10 tons. At first, we designed a 10-ton SMB by using critical

current performance of the conventional HTS wire and by the simulation method used on the design of the 4-ton SMB[2]. According to result of the first design, the 10-ton SMB consisted of a HTS magnet of 7 double pancake coils and a HTS bulk of 4 HTS plates. The SMB also needed to be cooled at less than 40 K. However, since the cost percentage of SMB was large in the whole flywheel cost, we tried to reduce number of the coils and quantity of the HTS wires substantially by using the high- I_c wire, which were manufactured by Superpower[5]. The high- I_c wire improved to 1.5 times higher I_c than the conventional HTS wire in magnetic field at 30 K to 50 K as shown in figure 8.

Figure 9 shows result of the FEM analysis of the SMB configuration that consists of 5 double pancake coils and 3 HTS plates. Inner side of the second upper coil was applied the highest magnetic field. Table 3 indicates the maximum magnetic fields of the coil in 4 tons, 10 tons and 15 tons loading respectively.

Table 3. The maximum magnetic field and coil current in the case of 4, 10 and 15 tons loading.

	4 tons	10 tons	15 tons
B_{\max} [T]	3.38	5.35	6.55
I_{coil} [A]	74	117	143

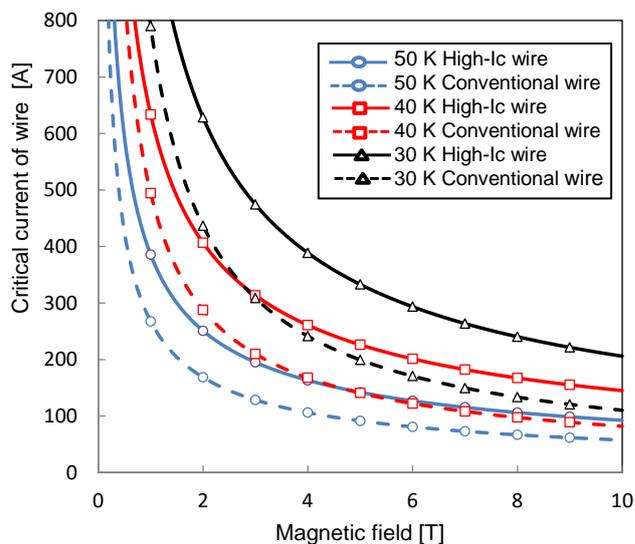


Figure 8. Critical currents of conventional REBCO wire (dotted lines) and high- I_c REBCO wire (solid lines), which were produced by Superpower.

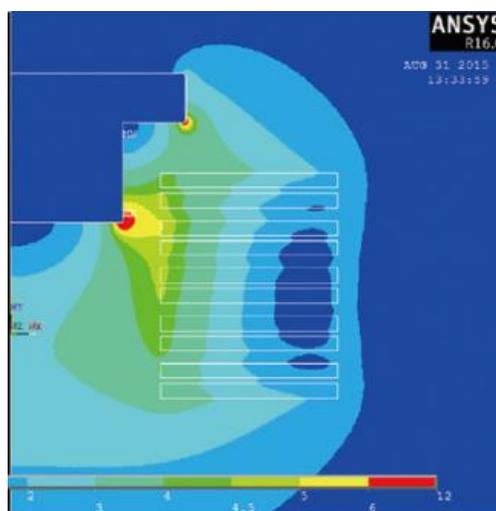


Figure 9. Electromagnetic analysis result for 5 double pancake coils and 3 HTS plates.

The load line in the second upper coil is indicated in figure 10. In the case of the SMB that provides 4-ton levitation, the conventional wire has enough I_c at 50 K, which we aim as the operation temperature. However, to realize 10-ton levitation, the conventional wire is cooled at 40 K. Moreover 15-ton levitation needs to cool the conventional wire at less than 30 K. On the other hand, high- I_c wire enables to lift the 10-ton rotor at 50 K. The 15-ton levitation is realized by cooling at 40 K in the high- I_c wire. In figure 10, The SMB that fabricated with the high- I_c wires is more stable and lower cost for cooling than the SMB with the conventional wires.

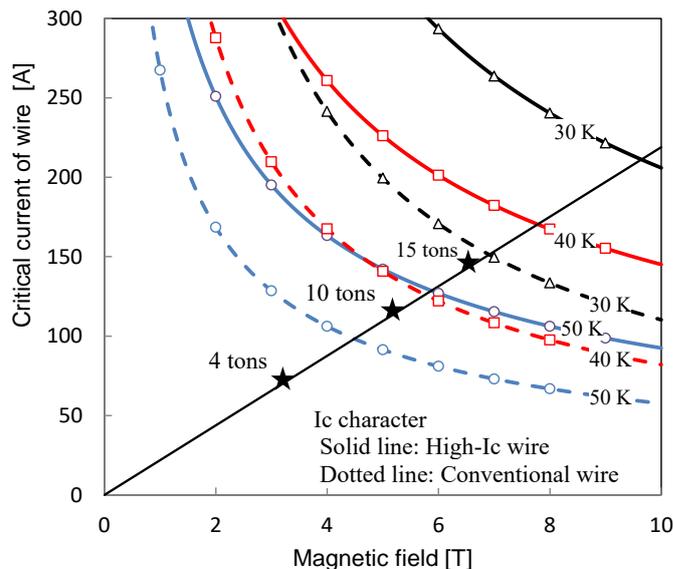


Figure 10. The load line of the 2nd upper coil and I_c characters of the conventional HTS wire and the high- I_c wire produced by Superpower.

Figure 11 shows the test equipment to measure levitation force with a load cell. A SMB for 10-ton levitation test was fabricated by using high- I_c wire to the 2 coils as shown in figure 11. Figure 12 shows test result of levitation force depending of the feeding current into the SMB magnet. The magnets were cooled at 25 K by the GM refrigerator. When the current of 126 A was applied to the magnets, the levitation force of 10 tons (98 kN) was achieved. The HTS bulk was assumed a perfect diamagnetism without magnetic field penetration in the magnetic analysis. Actually, when external magnetic field was increased, magnetic field was entered into surface of the HTS bulk. The difference between the analysis and the test result was caused by the magnetic penetration in the HTS bulk.

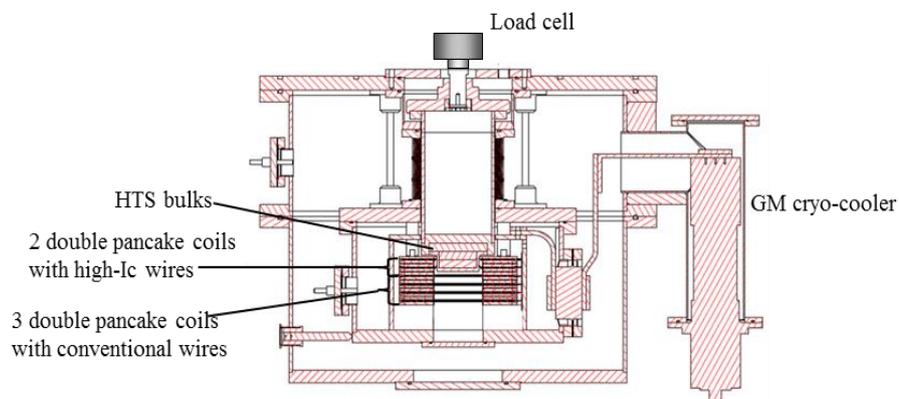


Figure 11. Configuration of 10-ton levitation test equipment.

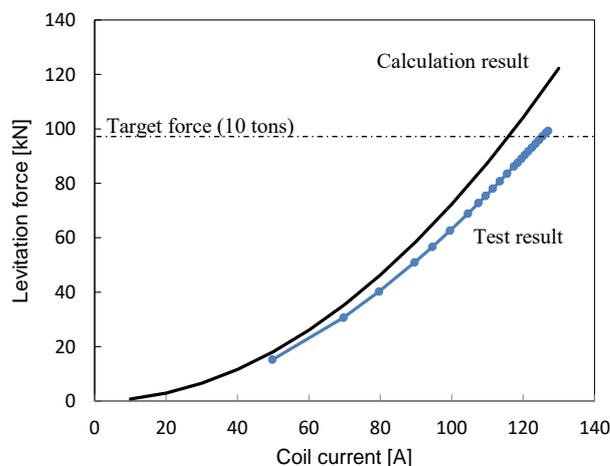


Figure 12. The levitation force depends on the coil current.

6. Summary.

The demonstration of the high temperature superconducting flywheel energy storage system (SFESS) using the superconducting magnetic bearing (SMB) was performed at Mt. Komekura in Yamanashi prefecture. The SMB composed of the HTS magnet and the HTS bulk levitate the 4-ton rotor in stable and safe.

The SMB with 10-ton levitation force was developed for the practical applications. In the first design, we needed 7 pieces of the HTS coils and 4 pieces of the HTS plates if we followed the 4-ton SMB design. In the final design, since the high- I_c wires were applied for the 10-ton SMB, the SMB that was composed of 5 pieces of the HTS coils achieved 10 tons in weight. This result led to reduce a cost of the SMB. Moreover, it introduces the other application such as a regeneration storage device of a railway. The regenerative device of the railway is needed with repetition of charge and discharge to more than 400,000 times and 1 MW class in power. The SFESS is the most suitable device against the requirements in energy storage devices. We started to study on the MW-class SFESS as the regeneration energy storage device while cooperating with related departments.

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References

- [1] Mukoyama S, Matsuoka T, Furukawa M, Nakao K, Nagashima K, Ogata M, Yamashita T, H, Hasegawa Yoshizawa K, Arai Y, Miyazaki K, Horiuchi S, Maeda T and Shimizu H 2015 *Physics Procedia*. **65** p 253
- [2] Nakao K, Kasahara H, Hatakeyama H, Matsuoka T and Mukoyama S 2016 *Furukawa Review* **47** p 13
- [3] Ogata M, Matsue H, Yamashita T, Hasegawa H, Nagashima K, Maeda T, Matsuoka T, Mukoyama S, Shimizu H and Horiuchi S 2016 *Superconductor Science and Technology* **29** 5
- [4] Teshima H and Morita M 2014 *Journal of Physics: Conference Series* **507** 012048
- [5] Nakasaki R, Zhang Y, Brownsey P, Sundaram A, Hazelton D, Sakamoto H and Fukushima T 2015 Continuous improvements in performance and quality of 2G HTS wires produced by IBAD-MOCVD for coil applications *MT-24 4OrBA_03* http://superpower-inc.com/system/files/2015_1018+MT24+4OrBA_03_0.pdf