Procurement of Nb_3Sn superconducting conductors in ITER

Yoshihiro NABARA, Takaaki ISONO, Yoshihiko NUNOYA, Norikiyo KOIZUMI, Kazuya HAMADA, Kunihiro MATSUI, Tsutomu HEMMI, Katsumi KAWANO, Yasuhiro UNO, Syuichi SEKI, Sachito ITO, Masayuki OSHIKIRI, Masatoshi YOSHIKAWA, Katsutoshi TAKANO, Humiaki TSUTSUMI, Yoshikazu TAKAHASHI, Hideo NAKAJIMA and Kiyoshi OKUNO

Japan Atomic Energy Agency, Naka, Ibaraki, Japan

(Received: 18 November 2009 / Accepted: 24 February 2010)

Superconducting strands are applied to Toroidal Field (TF) coil, Poroidal Field (PF) coil and Centre Solenoid (CS) in ITER. Japanese share of TF conductor is 25% and that of CS conductor is 100%. The conductor of TF coil contains 900 Nb_3Sn superconducting strands and 522 copper wires. As described in the length of superconducting strand, the length of Japanese share is 23,000km. In order to generate the magnetic field of which maximum value is 11.8T, 68kA of current is sent through the conductor under the rated operation. Although the critical current must be high, the high critical current tends to make the hysteresis loss rise at the same time. The hysteresis loss must be low because that is the heat generation under a fluctuating magnetic field. The strands which satisfy these performances compatibly had been developed. In advance of the other parties, the production of strands for TF coil started in 2008. To date, 3,400km long strands have been fabricated. Some of them are going to be cabled soon. The jacketing facility of TF conductor is being newly built. The building is almost completed. The procurement of strands for TF coil is underway.

Keywords: ITER, toroidal field coil, centre solenoid, Nb_3Sn superconducting strand, jacket

1. Introduction

Superconducting strands are applied to Toroidal Field (TF) coil, Poroidal Field (PF) coil and Centre Solenoid (CS) in ITER. Figure 1 shows the schematic view of these coils and Japanese share of these components. Japanese share of TF conductor is 25% and that of CS conductor is 100%. The procurement arrangement of TF conductor was concluded at the end of 2007 and the procurement of superconducting strands of TF coil started in 2008 in advance of the other parties [1]. The procurement arrangement of CS conductor will be concluded soon.

The configuration of TF conductor is illustrated in Fig.2. Main specifications of the conductor are shown in Table 1. The conductor contains 900 superconducting strands and 522 copper wires. The spiral channel is set at the centre of the cable to promote the coolant flow. Flowing in the spiral channel and between strands, the coolant of supercritical helium keeps the working temperature of 5.0K. In order to generate the magnetic field of which maximum value is 11.8T, 68kA of current is sent through the conductor under the rated operation. The current sharing temperature, which is the limitation of the temperature to maintain a superconducting state, is 5.8K. As the coolant temperature is 5.0K, the temperature margin is 0.8K. In one TF coil, 4,630m long TF conductors are wound with 134 turns into D-shape. As

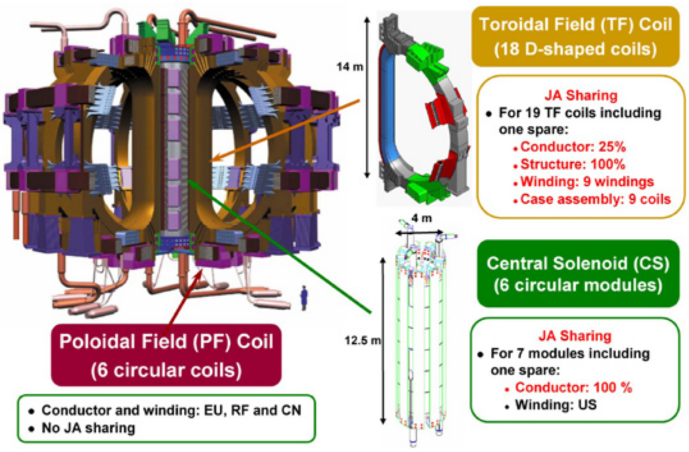


Fig.1 Superconducting coils in ITER and Japanese share of these components

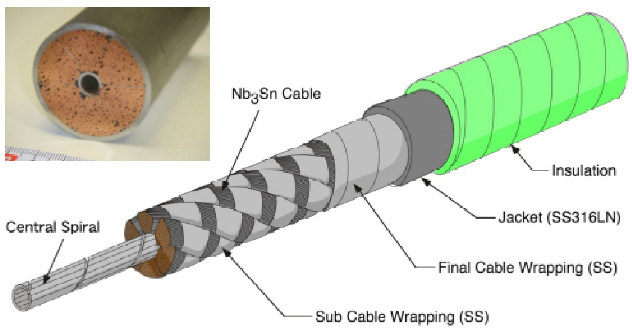


Fig.2 Configuration of TF conductor

author's e-mail: nabara.yoshihiro@jaea.go.jp

©2010 by The Japan Society of Plasma Science and Nuclear Fusion Research

described in the length of conductor, the length of Japanese share is 22km. As described in the length of Nb_3Sn strand, the length of Japanese share is 23,000km.

The manufacture of the TF conductor has three steps. First, large amount of superconducting strands are produced. Second, 900 superconducting strands and 522 copper wires are cabled. Finally, the cable is covered with the stainless steel jacket. This paper describes the present condition of the procurement of TF conductor on each step in Japan.

Table 1. Main specifications of superconducting conductor for TF coil

Item	Specification
Current	68.0 [kA]
Magnetic field	11.8 [T]
Working temperature	5.0 [K]
Current sharing temperature	5.8 [K]
Outer diameter of conductor	43.7±0.2 [mm]

2. Procurement of Nb_3Sn superconducting strand

The cross sectional view of the Nb_3Sn superconducting strand is illustrated in Fig.3. One strand has several km long. Main specifications on superconducting strand are shown in Table 2. The allowable margin of error of the strand diameter is only 0.01mm. The critical current I_c is the maximum current through the core region in Fig.3 as the superconducting state is maintained. Although the joule heating of a superconducting strand is zero under a steady state, the heating arises under varying magnetic field or current. The hysteresis loss is an index of this joule heating. Although the critical current must be high, the high critical current tends to make the hysteresis loss rise at the same time. The hysteresis loss must be low because that is the heat generation under a fluctuating magnetic field. It is difficult that the strand must satisfy these performances compatibly. The Cu in Fig.3 works as the stabilizer by circumventing current from Nb_3Sn superconducting filaments to Cu in case of breaking of the superconducting state. Thus the electrical resistivity of Cu must be low. Impurities in Cu markedly increase the electrical resistivity at the low temperature. In order to prevent Sn from diffusing to Cu, the sheet of Nb or Ta in Fig.3 works as the barrier. The residual resistivity ratio (RRR) of Cu is the ratio of the electrical resistance at 273K to that at 20K. In the mass production, these performances of superconducting strands vary each in spite of the same production way, as shown later.

The specifications of hysteresis loss and RRR are defined by the requirement of stability. The specification of I_c is defined as follows. At the beginning of the mass production of strand, the average critical current I_{c_ave} and that of standard deviation σ are calculated using the data

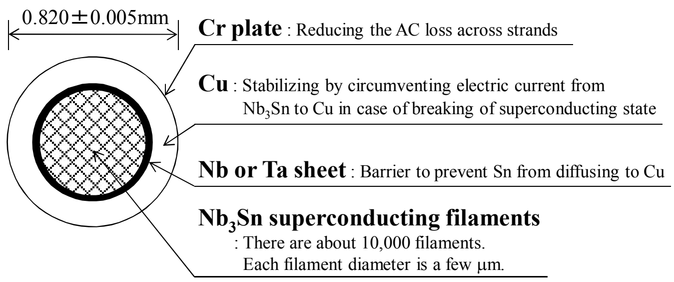


Fig.3 Cross sectional view of the Nb_3Sn superconducting strand

Table 2. Main specifications of superconducting strand for TF coil

Item	Specification
Strand diameter	0.820±0.005 [mm]
Critical current	> 202.2 [A] (for supplier A) > 212.5 [A] (for supplier B)
Hysteresis loss	< 500 [mJ/cm^3]
Residual Resistivity Rratio	> 100 [-]

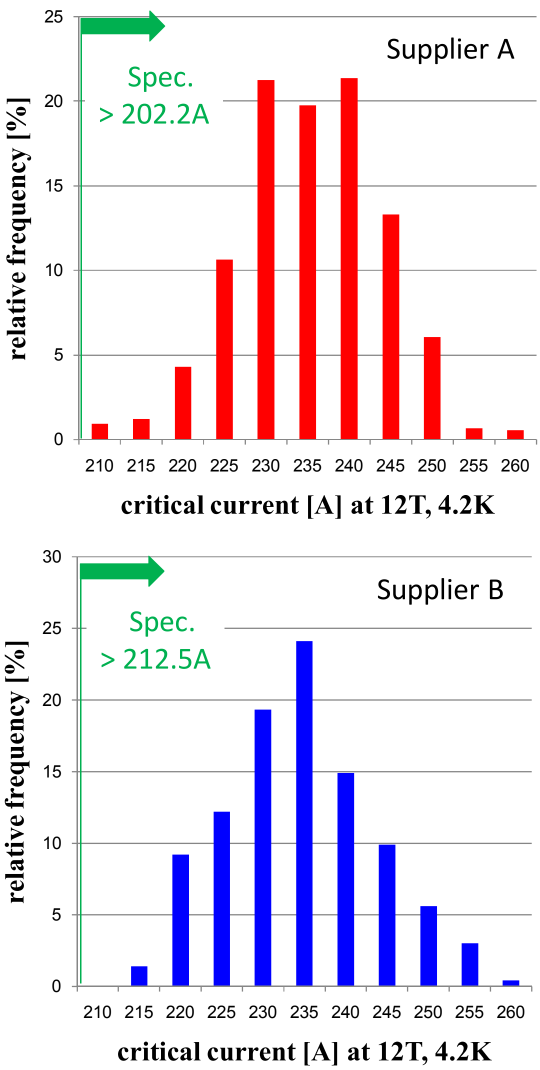


Fig.4 Critical current dispersion of fabricated superconducting strands on each supplier

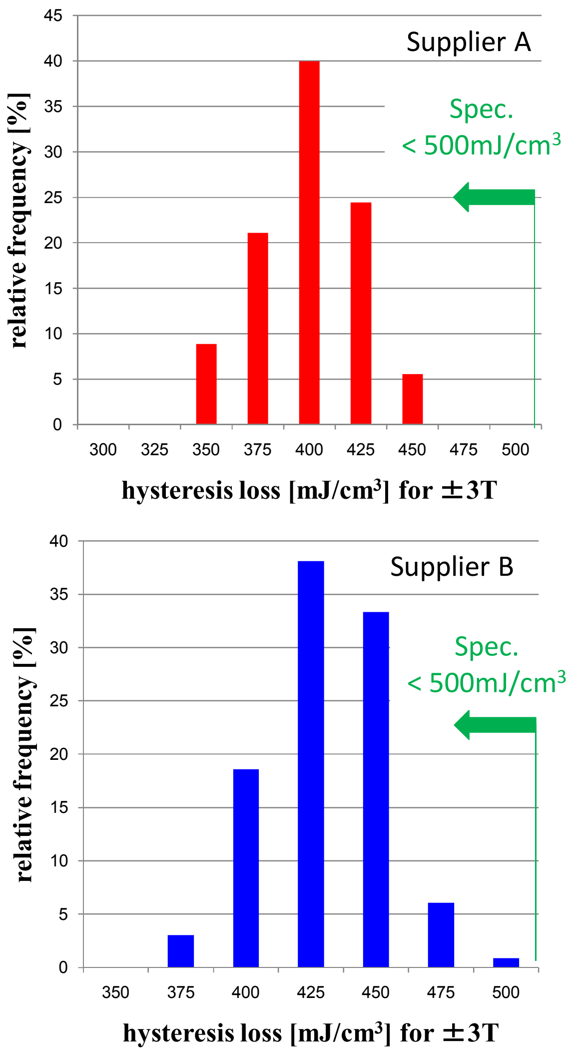


Fig.5 Hysteresis loss dispersion of fabricated superconducting strands on each supplier

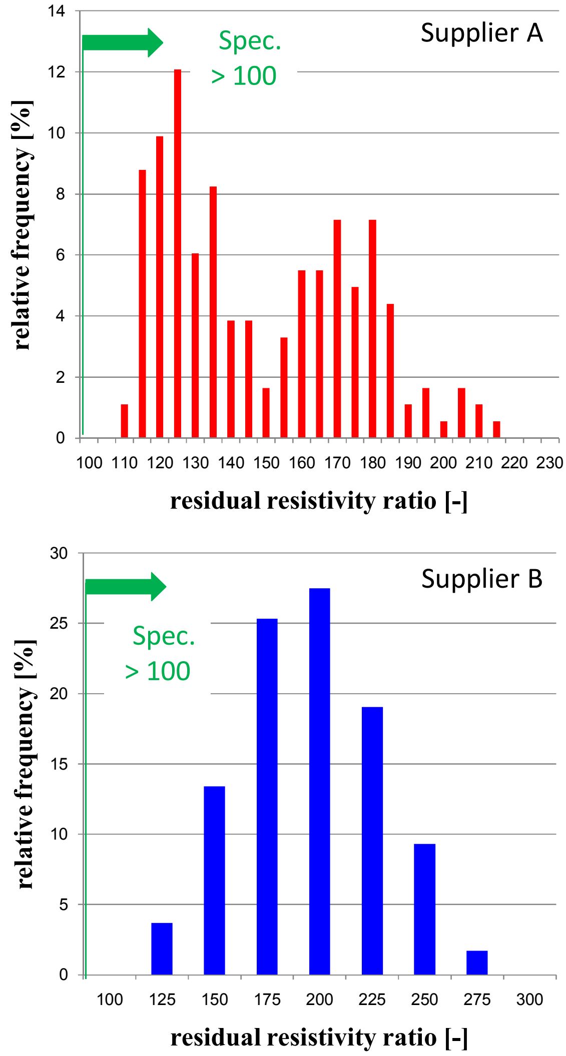


Fig.6 Residual resistivity ratio (RRR) dispersion of fabricated superconducting strands on each supplier

of the first production of 100km strand. The specification of critical current I_{c_spc} is defined as $I_{c\_spc} = I_{c\_ave} \pm 3\sigma$. Thus I_{c_spc} depends on a supplier. The values of I_{c_ave} and σ are revised after the production of 760km strand.

Two suppliers have been producing superconducting strands for TF coil so far. Figure 4 shows the critical current dispersion of fabricated superconducting strands each supplier. These data are higher than each specification. These histograms indicate that both suppliers' I_c have the peek at around 235A. Figure 5 shows the hysteresis loss dispersion of fabricated superconducting strands each supplier. These histograms point out that all data are lower than the specification of 500mJ/cm^3 and the supplier A tends to have more margins. Figure 6 shows the RRR dispersion of fabricated superconducting strands each supplier. All data are higher than the specification of 100. In the histogram of supplier A, two peaks appear at around 125 and 170, of which reason is not certain yet.

To date, 3,400km long strands have been fabricated and are ready to be cabled.

3. Cabling of Nb_3Sn superconducting strands

Geometric specifications of the superconducting cable for TF coil (TF cable) are shown in Table 3. The TF cable contains 900 Nb_3Sn superconducting strands and 522 cupper wires. The cabling process has five steps. Figure 7 illustrates the process. Two Nb_3Sn strands and one Cu wire are cabled into the 1st cable with a twist pitch of 80mm. Three 1st cables are cabled into the 2nd cable with a twist pitch of 140mm. Five 2nd cables are cabled into the 3rd cable with a twist pitch of 190mm. Five 3rd cables and one Cu sub-cable are cabled into the 4th cable with a twist pitch of 300mm. Six 4th cables are cabled into the 5th cable with a twist pitch of 420mm. The 5th cable also contains a centre spiral tube. These twist pitches are optimized through R&D. The allowable margin of error of the 5th cable diameter is only 0.5mm as shown in Table 3.

The technical difficulty is the large deformation of the six 4th cables on the last step to make six 4th cables to one 5th cable. Figure 8 shows the comparison between the cables for the CS model coil [2] assembled in 2000 and the cables for TF coil. The six solid circles are the cross section of the 4th cable before the last cabling process. The dotted circle is the diameter of the 5th cable. The circle in the centre is the centre channel. The diameter of centre channel for CS model coil is 12mm and that for TF coil is 9mm. The void fraction for CS model coil is 36% and that for TF coil is 33%. Thus, comparing the cable for TF coil with that for CS model coil, the density is thicker and the deformation is much larger. In the R&D of the cabling, some strands were kinked or crushed and some stainless steel wraps on the 4th cable of which thickness is 0.1mm were broken. Through the optimization of dies and rollers, these troubles did not occur throughout the cabling process.

Figure 9 shows the manufacturing facility of the 5th cable using the six 4th cables. Six 4th cables are supplied from the left side and are cabled with a twist pitch of 420mm. Through three dies and four rollers, the cable comes to be circle 41.8mm in diameter in precise with 0.5mm. The 5th cable is wrapped with the stain less steel sheet which has thickness of 1mm and wound on the round bobbin which has 1.9m diameter.

The 10m long conductor for the performance examination was manufactured without any problem. Using 1422 copper wires (with no superconducting strand), the trial manufacture of the dummy cable having 760m long has been successfully completed. The production of 760m long cables to be fabricated in TF coil will begin soon.

Table 3. Geometric specifications of the superconducting cable for TF coil

Item	Specification
Twist pitch of	
1st cable	80±5 [mm]
2nd cable	140±10 [mm]
3rd cable	190±10 [mm]
4th cable	300±15 [mm]
5th cable	420±20 [mm]
Diameter of 5th cable	41.8+0.2-0.3 [mm]

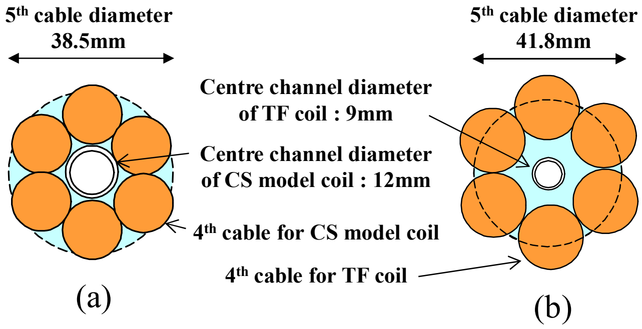


Fig.8 Comparison of six 4th cables before 5th cabling (a) for CS model coil and (b) for TF coil

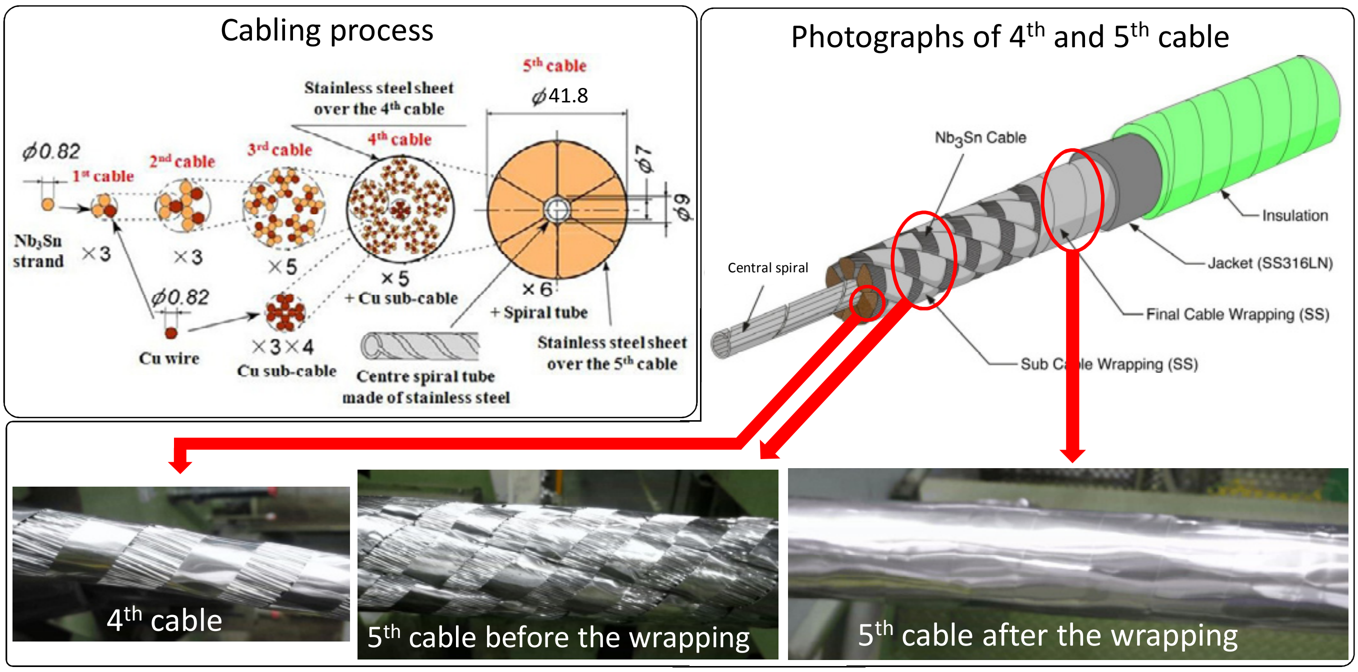
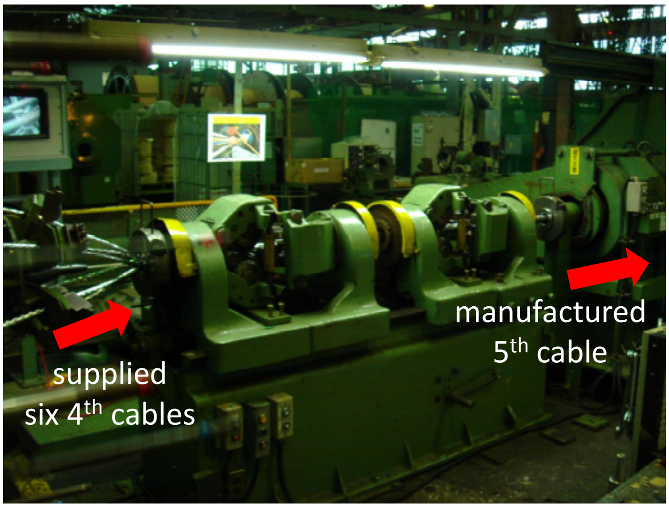


Fig.7 Constitution of the TF cable



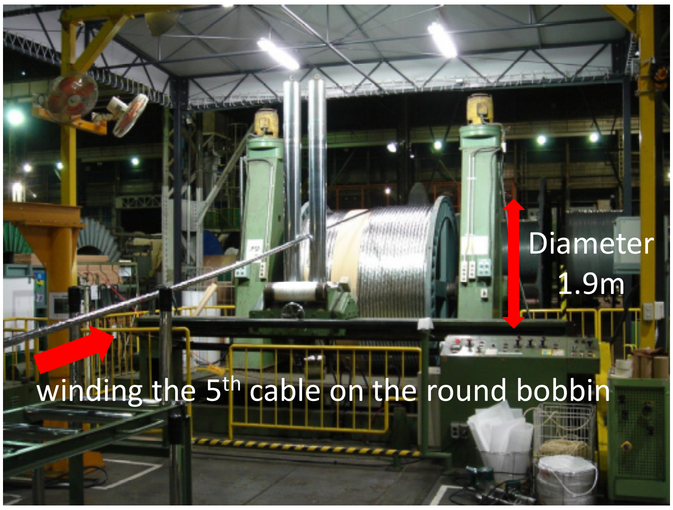


Fig.9 Cabling facility for cabling 5th cable

4. Jacketing factory of TF conductor

The jacketing factory is being newly constructed. The aerial photo is shown in Fig.10. The superconducting cable wound on the round bobbin is shipped from the cabling manufacturer to the building A in Fig.10. The superconducting cable is straightened in the line B. Welding 13m long jackets in series in the building C, the jacket comes to be 760m or 415m long. After the helium leak test of the welded jacket, the cable is inserted into the jacket. The cable and the jacket are combined into the conductor by the compaction machine shown at the bottom of Fig.10. Geometric specifications of the TF conductor are shown in Table 4. In the building C, the conductor is wound on the round spool which has 4m diameter. After the radio-transparency test and the helium leak test, the TF conductor is shipped to a TF coil manufacturer and wound into the D-shape of TF coil. Then the conductor is heat-treated at around 650℃ for about 10 days to produce the superconducting material of Nb_3Sn. This heat treatment also relieves the residual strain which is applied to the cable through the cabling, jacketing and winding processes.

The building is almost completed. Facilities are being set up steadily. Using the 760m long dummy cable made of 1,422 copper wires, the trial jacketing will be conducted soon. This facility is designed to be applicable to the jacketing of CS conductor as well.

Table 4. Geometric specifications of the TF conductor

Item	Specification
Thickness of jacket before compaction	1.9±0.1 [mm]
Outer diameter of jacket before compaction	48.0±0.2 [mm]
Outer diameter of conductor after compaction	43.7±0.2 [mm]

5. Summary

The present condition of the procurement of superconducting strands for TF coil is described as follows.

(1) Japanese share of Nb_3Sn strands for TF coil is 23,000km long. The production of superconducting strands has been started since 2008 by two suppliers. To date, those of 3,400km long have been manufactured. Although the performance of them varies in the mass production, all specifications are satisfied.

(2) The 10m long conductor for the performance examination was manufactured without any problem. Using 1,422 copper wires, the manufacture of the dummy cable which has 760m long has been successfully completed. The production of 760m long cables to be fabricated in TF coil will begin soon.

(3) The jacketing factory is being newly constructed. The building is almost completed. Facilities are being set up and will work soon. Using the 760m long dummy cable made of 1,422 copper wires, the trial jacketing will be conducted soon.

6. References

[1] Y. Takahashi et al., Abstracts of CSJ Conference **76**, 1B-a06 (2008).

[2] T. Ando *et al*., Journal of the Cryogenic Society of Japan **36**, 6 (2001).

Acknowledgements

The authors are grateful to thank Hitachi cable and Japan superconductor technology for manufacturing Nb_3Sn superconducting strand. We also wish to acknowledge Hitachi cable and J-Power systems on cabling strands. We are deeply indebted to Nippon steel engineering and Kobe steel for jacketing cables.

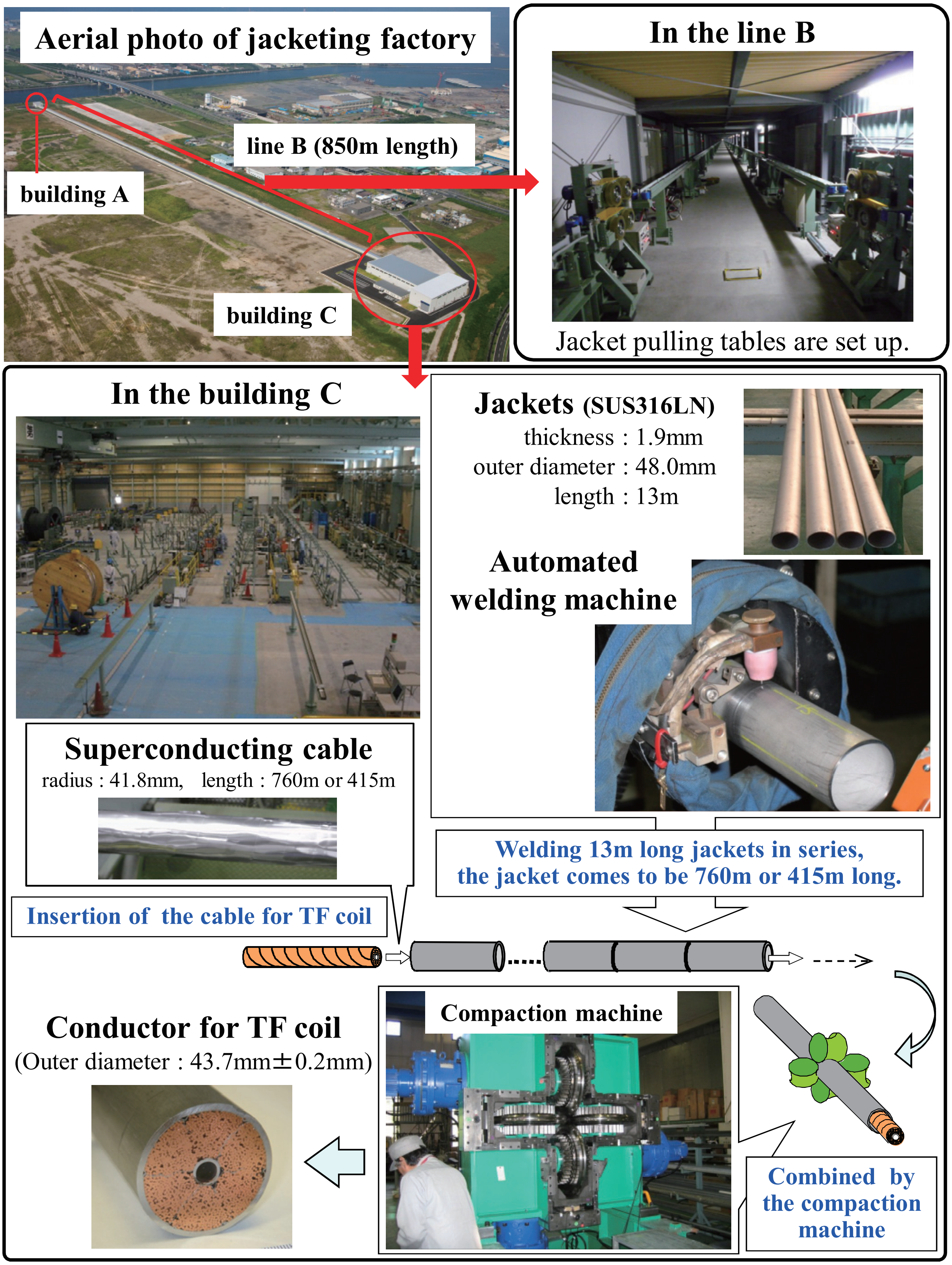


Fig.10 Jacketing factory of TF conductor