Development of Gap-filling Impregnation Method of ITER TF Coils

Mio NAKAMOTO*1,†, Yuma KASAI*1, Kazumi YOSHIZAWA*1, Kazuyuki SAKAMOTO*1, Norikiyo KOIZUMI*1, Masataka NAKAHIRA*1, Minoru YAMANE*2, Mitsuru HASEGAWA*2, Kengo OHASHI*2, Tsuneaki MINATO*2 and Kazuo KUNO *2

Synopsis: The ITER Toroidal Field (TF) coil is composed of a Winding Pack (WP) and a TF coil case (TFCC). In the manufacturing of a TF coil, the gap between the WP and the TFCC is filled with radiation resistant Triglycidyl-p-aminophenol (TGPAP) resin. Vacuum Pressure Impregnation (VPI) is adopted. The selected resin system displayed two potential problems: high viscosity and cracking after cure. A series of production optimizations have been performed to develop techniques to apply the selected resin for the TF coil production: crack countermeasure, narrow gap injection, and pressure control. For crack countermeasure, the addition of fiberglass tape or sheet layer was found to be effective in preventing fragmentation of cracked resin. Since the cracked resin would not harm the TF coil quality as long as it stays in the original position, addition of confining fiberglass layers solves the problem. In narrow gap qualification tests, resin injection into a 2 mm wide space was observed with proper selection of fiberglass layer addition conditions. The pressure qualification test showed that resin cured without additional pressurization can satisfy the compression strength requirements. From those results, techniques for the TF coil production have been developed, and with the implementation of those techniques the gap-filling of the first TF coil in Japan was successfully completed in 2019. Since then, two more TF coils have completed the gap-filling process with some improvements.

Keywords: ITER, TF coil, impregnation, VPI

(Some figures in this article may appear in color only in the electronic version)

1. Introduction

The ITER Toroidal Field (TF) coil is composed of a superconducting Winding Pack (WP) enclosed in a stainless-steel case, the Toroidal Field Coil Case (TFCC) [1]. In the last step of TF coil fabrication process, the WP is integrated with the TFCC. First, the WP is positioned carefully within the TFCC sub-assembly, the TFCC is closed by welding, and the gap between the WP and the TFCC is filled with resin to confine them. At the end, some surfaces of the TFCC are machined to their final shape.

The gap-filling resin serves two purposes in the TF Coils: 1) to transmit the electromagnetic force on the WP during operation to the TFCC, and 2) to fix the WP position relative to the TFCC. Considering the operating conditions of TF coils, the material properties of gap-filling resin were determined [1]. Also, to maintain the insulation quality of ground insulation for the WP, the cure temperature of gap-filling resin must be kept below the glass transition temperature \( T_g \) of cyanate ester used for the ground insulation, which is \( 150^\circ\text{C} \) [2]. There has been a case of coil failure in the NSTX-U Project [3] due to imperfect insulation in the conductor pack. The gap-filling process must be planned to avoid any damage of the ground insulation of the WP. The specification for gap-filling resin is summarized in Table 1.

Considering those specifications, Triglycidyl-p-aminophenol (TGPAP) with Diethyl toluene diamine (DEDTA) hardener was chosen for its resistance to radiation, and additional filler was introduced to match the integrated thermal contraction (ITC) of resin to that of stainless steel in order to prevent the cracking of resin [4]. Since the material properties of the resin system have been qualified, the next step was to qualify the selected resin system for the application to the TF coil manufacturing. As production qualifications, 3 main tests were performed; 1) crack countermeasure, 2) narrow gap resin injection, and 3) pressure optimization.

In this paper, results of those production qualification
tests are reported. Then, the gap-filling techniques are described. These techniques have been applied in TF coil manufacturing and three of nine TF coils have completed the gap-filling process. We report the gap-filling results of those three coils.

2. Resin Qualification for TF Coil Production

2.1 Selected resin characteristics

Even though the filler material for gap-filling resin was selected considering the resin flow\(^1\), the addition of filler caused a large increase in viscosity. Figure 1 shows the change in mixed resin viscosity in time. Since the mixed resin maintained the best viscosity at 40°C, resin injection temperature is set at 40°C. The viscosity of the filler-charged resin is 10 Pa·s when mixed, and increases as a cubic polynomial in time. At 24 hours after mixing, the viscosity reaches 26 Pa·s. The flow of filler-charged resin was confirmed for the nominal 7-11 mm gaps between the WP and the TFCC previously; however, the additional qualification was necessary to confirm successful resin injection into the narrowest gap.

In previous studies, some tests were performed to determine techniques to minimize cracking of the resin. The temperature change rate was limited to below 5°C per hour. Also, the cure temperature was reduced to 75°C to reduce strain in resin as shown in Fig. 2. The cure cycle temperature and the pressure were selected through the resin qualification tests. The mixing ratio of resin components was finalized (Table 2) to match the ITC ratio of the mixed resin to that of the WP and the TFCC so that the gap-filling resin would contract the same way as the TFCC and WP when TF coil is cooled to its operational temperature of 4 K. Even at the best effort, the resultant ITC of filler-charged resin was 0.44%, while that of stainless steel is 0.29\(^%\). This 0.15% difference left a concern of resin cracking.

2.2 Crack countermeasure

During TF coil energization, a WP and a straight portion of a TFCC deform by its own electromagnetic force. A debonding agent is applied on the surface of the WP to allow open and close of the gap between the WP and the TFCC without damaging the ground insulation. Because of the debonding agent on the WP side, a gap-filling resin bonds to the TFCC. From structural analysis result, a maximum of 4.2 mm gap is expected between a WP and the gap-filling resin (Fig. 3). The gap-filling resin only undergoes compression stress, so cracked resin will be a problem in the TF coil only if a cracked fragment dislodged and fell into a gap between the WP and the TFCC (Fig. 4). As production qualification, prevention measures for resin crumbling were considered.

![Gap-filling Process](image)

**Fig. 2** VPI process and cure cycle plan of TF coil gap-filling impregnation. Resin is injected around 45°C and cured at 75°C. After resin injection, resin is pressurized with 0.2 MPa and cured at 0.1 MPa.

| Table 1  | Specifications for gap-filling resin. |
|---------|--------------------------------------|
| Radiation Resistance | 1x10\(^7\) Gy |
| Cure Temperature | <150°C |
| Pot Life | ~40 h |
| Integrated Thermal Contraction | 0.44% (target: 0.29%) |
| Compressive Strength | 200 MPa @ 4 K |

**Fig. 1** MY0510 Gap-filling resin viscosity change in time at 40°C. The data was fitted with vertical axis as Y and horizontal axis as x.

| Table 2  | Components of resin and mixing ratio. |
|---------|---------------------------------------|
| Components | Mixing Ratio |
| Resin: Aradite® MY0510 (TGPAP) | 38.11 vol% |
| Hardener: ARADUR® 5200US (DEDTA) | 19.89 vol% |
| Filler: Microlod H400 (Dolomite) | 41.00 vol% |
| Anti-setting agent: Attagel® 40 (Calcined clay) | 1.00 vol% |
2.2.1 Test setup
As crumbling prevention, wrapping the WP with fiberglass tape around the WP and attachment of fiberglass sheets on the inner surface of the TFCC were considered. To verify its effectiveness, impregnation tests were done with a stainless-steel WP mock-up in a stainless-steel box with impregnation gaps (Fig. 5). Two identical test models were prepared. For each model, half of the WP mock-up was wrapped with the 0.25 mm thick S2 fiberglass tapes with half-overlap. One of the models underwent thermal shock test by immersing into liquid nitrogen after curing.

2.2.2 Test result
Some resin cracking was observed in all models regardless of whether fiberglass tape layers were used, or whether they underwent the thermal shock test. However, the cracked pieces of the resin remained well attached to the models with fiberglass tape layers, and it was not possible to peel off the cured resin even with the wedged tool (Fig. 6).

2.2.3 Conclusion from crack countermeasure test
Since the addition of fiberglass layers prevented the fragmentation of cracked resin, it has been adopted into TF coil production. From a mechanical analysis, the deformation of a TF coil during its operation was studied to locate where the gaps would be generated (Fig. 3). In those areas the WP is wrapped completely with fiberglass tapes and some fiberglass sheets are attached to the TFCC. However, these additional fiberglass layers might

---

**Fig. 3** Assessment result of the gap between gap-filling resin and TFCC during TF coil operation.

**Fig. 4** Crumbling of cracked resin. During TF coil operation, around 4 mm of gap is expected between a WP and a gap-filling resin due to deformations of the WP and the TFCC.

**Fig. 5** Crumbling prevention test model. Upper figure shows the cross sectional view of the lower figure at the A-A' line, where a fiberglass sheet was wrapped on the WP model.

**Fig. 6** Crumbling prevention test result. No resin crumbling occurred in the right half of the model, where the fiberglass tape was wrapped on the WP model section, while crumbling occurred in the left half. The cured resin would not be fragmented even when chisel was inserted between the model and the resin.
prevent flow of resin into narrow gaps between the WP and the TFCC. Before application to the actual TF coil production, qualification tests were performed to verify the resin injection into narrow gap with additional fiberglass layers.

2.3 Narrow gap qualification

For the TF coil production, there is 4 mm minimum gap requirement between the WP and the TFCC. In previous tests, the gap was assessed to satisfy the requirement, even with the welding deformation due to closure welding of the TFCC. The misalignment between the WP profile and its current center line (CCL) was found to be larger than expected, leading to a possibility that the minimum gap might be as small as 2 mm in some portions of the coil.

Another concern arose from the outcome of the crumbling prevention tests. As mentioned previously, the resin was observed to completely impregnate the fiberglass layers, leaving the filler in the gap. Considering the increase in overall resin viscosity, if the proposed fiberglass tape wrapping covered the entire WP the impregnation qualification would need to be performed under the fiberglass tape wrapping conditions. However, attachment of fiberglass sheets on the inner surfaces of the TFCC is only suggested in the area where the large gap is expected. Therefore, the impregnation qualification with the fiberglass sheet attachment is not necessary.

2.3.1 Test setup

To qualify the resin injection into narrow gap with fiberglass tape layers for resin crumbling mitigation, some tests were performed. The models for the tests are shown in Fig.7. Each model is composed of shallow stainless-steel box with transparent cover. The mock-up of the WP is a stainless-steel plate wrapped with fiberglass tape. The thickness of the WP mock-up was adjusted to modify the resin injection gap for test. The length of each model is 1.5 m with resin inlet at the bottom to create the laminar flow as in the actual gap-filling situation.

Since the viscosity of the mixed resin increases exponentially with the duration from mixing, one concern is whether the resin injection can resume after an emergency stop. To simulate the emergency condition, the resin was injected from the inlet hole of the model until half of the model was filled, then the resin injection was resumed from the same resin inlet after a 24-hour pause. During the pause, the temperature of the model was maintained at 40°C with evacuation to 100 Pa. To visualize the flow of resin, black dye was added into the fresh resin mixed for the second day while the resin for the first day was left at the natural color.

2.3.2 First test result

In the first test, a model with a 2 mm gap was used (Model No. 1). One layer of 0.25 mm thick fiberglass tape was wrapped on the WP mockup with half overlap. In the TF coil production, the cylinder pumps operate at 1.4 MPa. Considering the pressure drop in the resin injection line, the pump enables 0.04 MPa normal injection pressure and 0.1 MPa maximum at the resin inlet hole on the TFCC. Therefore, for the test, the resin injection was performed with injection pressure of 0.04 MPa absolute pressure on the first day. The resin level increased faster at the edges of the model. Since the resin flows in from the sides, it created a large void at the center portion (Fig. 8). After 30 minutes, the resin flow decreased. The injection pressure was gradually increased to a maximum operating pressure of 0.2 MPa absolute pressure. The resin level at the sides was
able to reach the half of the model height as planned; however, the resin level at the center remained lower and large voids existed. The model was left in this state for 24 hours at 40°C with evacuation. On the next day, many voids were still present in the resin. The conclusion from this test is that resin injection at 0.2 MPa absolute pressure is not possible.

The uneven resin injection was caused by the larger gaps at the sides of the WP mockup. For the following tests, fiberglass yarn was implemented to reduce the gap difference. We also noticed that the boundary of next fiberglass tape layer impedes the resin flow. In the first model, the fiberglass tape was wrapped in direction of flow, which acted as a filter for the filler in the resin (Fig. 9); this created filler-rich viscous resin at the fiberglass tape boundary. We determined that it is this effect that prevents the resin flow.

2.3.3 Second test

In the second test, the direction of fiberglass tape wrapping was specified so that the fiberglass layers are in the direction of resin flow. Since thicker fiberglass tape soaks up more resin, thinner fiberglass tape is preferable to prevent the thickening of remaining resin. The subsequent tests were performed with models No. 2-5. The results of all the tests are summarized in Table 3.

Even if the fiberglass tape is wrapped in the resin flow direction, when 0.25 mm thick fiberglass tape was used the resin did not flow into the 3 mm gap on the second day (Model No. 3). With thinner fiberglass tape, the resin was able to flow into even narrower gap of 2 mm (Model No. 2 and 5). Therefore, it was concluded that both the thickness of the fiberglass tape applied and the direction of fiberglass tape wrapping were important factors for proper resin flow.

2.3.4 Conclusion from narrow gap qualification tests

From the narrow gap qualification tests, the conditions for successful gap filling with the resin crumbling mitigation were clarified: the resin can fill a 2 mm narrow gap even after 24 hours of pause if an absolute pressure of 0.1 MPa is applied. Also, the specifications of the resin crumbling mitigation measure were defined; 1) the fiberglass tapes applied on the WP shall have a thickness of 0.13 mm and 2) the direction of fiberglass tape wrapping should not interfere with the resin flow.

In actual production, 0.13 mm thickness fiberglass tapes are wrapped on the WP with half over-lap to cover the whole surface of WPs before integration into the TFCC. For the TFCC, STYCAST epoxy is used for the attachment of fiberglass sheets only at the areas of concern. Because of the STYCAST epoxy, gap-filling resin would not soak into the sheets. Moreover, the locations of fiberglass sheets are where the gap between the WP and the TFCC is large.

![Fig. 9 Resin flow and fiberglass layer directions. The figure in left shows the fiberglass layer is wrapped in a direction against a resin flow while the one in right is along the resin flow.](image)

![Fig. 10 Locations of resin inlets and outlets. V1 to V12 are resin inlets. V13 and V14 are resin outlets. Ones in parentheses are located on the opposite side.](image)

---

**Table 3** Narrow gap qualification test summary.

| Test No. | Gap (mm) | Fiberglass tape thickness (mm) | Fiberglass layer direction | Resin injection pressure (MPa) |
|----------|----------|------------------------------|---------------------------|-------------------------------|
|          |          |                              |                           | 1<sup>st</sup> day | 2<sup>nd</sup> day |
| 1        | 2        | 0.25                         | Against flow              | N.A.                        | N.A.                   |
| 2        | 2        | 0.13                         | In flow                   | 0.04                        | 0.2                    |
| 3        | 3        | 0.25                         | In flow                   | 0.04                        | N.A.                   |
| 4        | 4        | 0.25                         | In flow                   | 0.04                        | 0.2                    |
| 5        | 2        | 0.13                         | In flow                   | 0.04                        | 0.1                    |

* N.A. indicates the resin injection with proper pressure was not possible.
of resin before curing. 4) Finally, the resin is cured at atmospheric pressure (0.1 MPa).

The WP of a TF coil is enclosed in a TFCC except at the cooling pipe extraction of the TFCC and the terminal region of the WP, where conductor joints are extracted from the WP for internal and external connections. As shown in Fig. 11, the opening of TFCC at the terminal region does not have uniform width. Also, groups of 14 mm O.D. cooling pipes positioned with a 22 mm pitch penetrate. Those gaps shall be sealed to endure the vacuum-pressure cycle of gap-filling impregnation.

2.4 Gap seal test

At the terminal region, the total pressure (absolute pressure) amounts to the pressurization amount (gage pressure) plus the pressure due to weight of resin, 0.13 MPa. For the terminal region, a seal structure with rubber sealants and pressing jigs was designed. Pressurization qualification tests were performed to confirm the validity of the seal structure. First, it was tested with a simple small size mock-up, then followed by full-scale mock-up. For the full-scale mock-up, the half of the actual terminal region was reproduced.

2.4.1 Gap seal test results

The proposed seal design was able to withstand the evacuation to 10 Pa with leak rate of $1.5\times10^{-9}$ Pa·m$^3$/s and the pressurization to 0.35 MPa with leak rate of $9.2\times10^{-3}$ Pa·m$^3$/s for the simple model. The leak rates are equivalent values at 20°C. The simple model showed acceptable results; however, for the full-scale mock-up, the leak rates are much larger. The model was only evacuated down to 150 Pa with leak rate of 0.44 Pa·m$^3$/s and the pressurization up to 0.28 MPa with leak rate of 535 Pa·m$^3$/s. The outcomes are summarized in Table 4.

2.4.3 Conclusion from pressure qualification test

Since excessive pressurization may cause the breakage

![Fig. 11 Terminal region of TF coils. A WP is completely enclosed in a TFCC except at the terminal region. All the instrumentation and electrical connections to the WP are extracted here along some cooling pipes for the TFCC.](image)

For those reasons, the thickness of the fiberglass sheets on the TFCC would not interfere with the gap-filling process; therefore, 0.25 mm thick fiberglass sheets are selected.

There are multiple resin injection inlets in a TF coil, located over the whole range of TFCC with 1.5 to 2.5 m intervals (Fig. 10). The resin is initially injected from the lowest inlets of the TFCC; when the resin level reaches the level of the next inlets, valves to those inlets are also opened. By changing the inlet positions according to the resin level, the low viscosity is maintained at the resin front. With this concept, the complete filling of the gap will be realized.

### Table 4  Gap seal qualification test summary.

| Model  | Test          | Internal Pressure | Leak Rate* (Pa·m$^3$/s) |
|--------|---------------|-------------------|--------------------------|
| Simple | He Leak Test  | < 10 Pa(a)        | $1.5\times10^{-9}$       |
|        | Pressurization| 0.2 MPa(G)        | $5.4\times10^{-5}$       |
|        |                | 0.35 MPa(G)       | $9.2\times10^{-5}$       |
| Full-  | He Leak Test  | 150 Pa(a)         | 0.44                     |
| scale  | Pressurization|                  |                          |
|        |                | 0.1 MPa(G)        | 0.6                      |
|        |                | 0.15 MPa(G)       | 3.0                      |
|        |                | 0.2 MPa(G)        | 41.8                     |
|        |                | 0.25 MPa(G)       | 286                      |
|        |                | 0.28 MPa(G)       | 535                      |

*Leak rates are converted into 20°C. Pa(a) indicates absolute pressure. Pa(G) indicates gauge pressure.
of the seal between the WP and the TFCC, 1) optimization of the pressurization and 2) balancing the internal and external pressure at the gap seal were considered.

For pressure optimization, the minimum pressure was determined to be 0.1 MPa since the results of narrow gap impregnation tests showed that at least 0.1 MPa of absolute pressure is necessary to achieve complete gap filling in the case of a 24-hour pause. Compression tests were performed on five resin samples which were cured at atmospheric pressure without additional pressurization. The results ranged from 440 to 470 MPa at 4 K, satisfying the compressive strength requirement of 200 MPa.

For balancing the pressure difference over the gap seal, stainless-steel structures to enclose the whole cooling pipe penetration parts and the whole terminal region were designed\(^7\). By adjusting the pressure inside this terminal cover to the same pressure inside the TFCC, the pressures on the both sides of the terminal region can be maintained at the equilibrium.

3. Application to TF Coil Production

From the qualification tests, techniques have been developed to create a gap-filling layer with necessary strength. However, as described in the beginning, the gap-filling resin also provide a function to fix the WP position within the TFCC. The positioning of the WP in the TFCC is finalized before the gap-filling operation and the positional information of the WP is transferred to the reference points on the TFCC surface\(^6\). Thereafter, the positional relationship of the WP and the TFCC shall be maintained through the gap-filling operation.

During the VPI operation, evacuation before resin injection and pressurization after resin injection have the potential to move the WP. Also, temperature expansion must be the controlled to keep the relative position of the WP to the TFCC. Therefore, two parameters which impact the relative position of the WP to the TFCC in the VPI are:

1) pressure difference over the terminal region
2) temperature difference between the WP and the TFCC.

Those parameters are monitored and controlled during the VPI operation.

3.1 Procedure and instruments

Applying the techniques developed previously, the gap-filling operation proceeds as follows:

1) Application of fiberglass layers on the WP and the TFCC,
2) Installation of sealing structures at the terminal opening, sealing boxes over the cooling pipes, and the terminal cover over the whole terminal region,
3) Evacuation inside the TFCC,
4) Resin injection into the TFCC from the injection holes at 40°C,
5) Pressurization to 0.2 MPa,
6) Gelling of resin at 65°C at atmospheric pressure,
7) Curing of resin at 75°C at atmospheric pressure, and
8) Cooldown.

Even though the pressure qualification test showed that 0.1 MPa pressurization is sufficient to achieve the necessary compressive strength of resin, the pressurization parameter for TF coil production was kept on the conservative side, at an absolute pressure of 0.2 MPa, since the gap-filling operation is only parameter-controlled and not reversible or repairable.

The pressure difference over the terminal seal is controlled by feeding pressurized nitrogen gas into the terminal cover. The target difference is set to a maximum of 50 kPa to maintain the equilibrium. Pressure control is performed during resin injection and pressurization. During gelling and curing, the both internal and external spaces are opened to atmospheric pressure.

Joule heating of conductors controlled the temperature of the WP, while the temperature of the TFCC is controlled by flowing temperature-controlled water through its internal cooling pipes\(^7\). Since the both components are mainly made of stainless steel, the temperature difference shall be maintained below 2.5°C to keep the differential thermal expansion less than 300 μm during resin injection. The relative displacements of the WP to the TFCC are monitored with micro sensors installed at the terminal region.

3.2 Gap-filling Results

In August 2019, the developed impregnation method was successfully applied to the first TF coil in Japan. Since then, gap-filling of two more coils have been performed. The injection speed of the resin was controlled by the cylinder pumps to 0.62 L/min to fill a 1500 L gap. The resin injection into the TFCC was completed in 70 hours for the first coil due to unexpected pauses caused by system errors. In the gap-filling of the following coils, the injection times were improved to 46-49 hours by reducing the delays due to control system errors.

The temperature control result for the first coil is shown in Fig. 12. The result shows the temperatures are controlled within the target range for each stage. During the temperature-hold time, the temperature is adjusted near the maximum range so that the temperature raise duration for next step can be minimized. Similar results were obtained for the following coils.
The pressure control result of the first coil is shown in Fig. 13. As the resin level inside the TFCC increases, internal pressure at the terminal region increases due to the weight of resin. The pressure difference shall be balanced at the terminal region; however, if the internal pressure become smaller than the external pressure, there is a risk that some air will be drawn into the TFCC. To avoid such situation, the external pressure was kept 20 kPa lower than the internal pressure.

There are two outlet holes located at the top of the TFCC (V13 and V14 of Fig. 10). The diameter of the outlet holes is only 10 mm while the injection holes are 22 mm. When the resin level reached the outlet holes, the internal pressure of resin suddenly increased, resulting in the sudden increasing in the pressure difference at the terminal seal at 88 hours in Fig. 13. Momentarily, the relative displacement of the WP exceeded 300 μm, which is the target limit for the quality control. However, prior to the temperature increase for curing, the relative displacement was returned to 200 μm, the acceptable level of displacement.

For the subsequent coils, a buffer tank was added between the cylinder pumps and the TFCC. By maintaining the constant pressure at the buffer tank, the internal pressure of resin was controlled. As a result, the relative displacements of the WP for the second and the third coils were improved to below 100 μm.

### 4. Conclusion

TGPAP with dolomite filler was chosen as material for gap-filling of the ITER TF coils because of its resistivity to radiation. However, the selected resin showed some concerning properties such as the high viscosity and a risk of cracking. A series of qualification tests, which include crack countermeasure, narrow gap qualification, and pressurization qualification, were performed to find solutions to those shortcomings. As the results, the importance of the direction of fiberglass layer direction and the monitoring and control of temperature and pressure during VPI process were realized. The techniques developed through those tests have compensated for the concerning properties of the resin and allowed this radiation resistant TGPAP based resin to be adopted in the TF coil production successfully. The application of those techniques would not be limited to ITER TF coils but can be applied to other types of resins to minimize the void formation or prevent the resin fragmentation, which may result in coil failure.

### Acknowledgments

The author would like to thank Mitsubishi Electric Corp. for their contribution in the gap-filling process qualification and implementation to manufacturing. Without their hard work, the series production of TF coil would not be realized.
References

1) E. Baynham, et al.: “The insertion of the WP in the structural casing of the TF coils of ITER,” IEEE Trans. Appl. Supercond. 20 (2010) 389-393
2) M. Hooker, J. Walsh, M. Haynes and N. Munshi: “Design and testing of ITER TF coil insulations,” IEEE Trans. Appl. Supercond. 21 (2011) 3127-3131
3) J. R. Petrella, et al.: “Forensic analysis of faulted NSTX-U inner poloidal field coil,” IEEE Trans. Plasma Sci. 46 (2018) 2653-2662
4) S. J. Canfer, et al.: “Development of a filled resin system for the TF coils of ITER,” Fusion Eng. Des. 86 (2011) 2504-2507
5) N. Koizumi, et al.: “Development of ITER TF coil winding pack (WP) and qualification for assembling WP and coil case in Japan,” IEEE Trans. Appl. Supercond. 29 (2019) 4200505
6) M. Nakamoto, et al.: “Development of ITER TF coil assembly technique, Integration of winding pack into coil case,” TEION KOGAKU 55 (2020) 400-408
7) N. Koizumi, et al.: “Progress of ITER TF coil fabrication in Japan,” IEEE Trans. Appl. Supercond. 30 (2020) 4202106

Mio NAKAMOTO Mio Nakamoto holds a Bachelor in Science in Physics from University of California, Los Angeles. She joined National Institutes for Quantum and Radiological Science and Technology (QST) in 2015 as a temporary staff. In 2018, she became the full-time staff and appointed as the responsible person for WP integration of TF coils.

Yuma KASAI Yuma Kasai graduated from Tohoku University and joined Mitsubishi Electric Corporation in 2013. He served for manufacturing of ITER TF coil and superconducting device. Currently, he works at QST as a Part-time Researcher.

Kazumi YOSHIZAWA Kazumi Yoshizawa joined QST in June 2017. He is mainly engaged in development of superconducting coils.

Kazuyuki SAKAMOTO Kazuyuki Sakamoto joined QST in May 2017. He is in part of integrating TF coils and transport frames for TF coils.

Noriyuki KOIZUMI Born in May 1964. He graduated from Waseda University and joined Japan Atomic Energy Agency (JAEA) in 1990. He has been engaged in research and development of superconductors and magnets for nuclear fusion reactor use. He holds a Ph.D in Engineering.

Masataka NAKAHIRA Born in March 1967. Holding a Doctor of Engineering from Tsukuba University, received in 2004. He joined the superconducting magnet technology group in JAEA / QST from 2013, after 5 years employment at ITER, France. He works as a group leader of the superconducting magnet technology group since 2019. He worked for ITER since 1992 starting from JAERI.

Minoru YAMANE Minoru Yamane joined Mitsubishi Electric Corporation in 1985 and has been engaged in the design of Nuclear Fusion experimental devices.

Mitsuru HASEGAWA Mitsuru Hasegawa holds a Doctor in Science in Physics from Nagoya University, Japan. He joined Mitsubishi Electric Corporation in 1985 and has been engaged in the design of magnetic coils of Nuclear Fusion experimental reactor.

Kengo OHASHI Kengo Ohashi joined Mitsubishi Electric Corporation in 1971 and has been engaged in the design of Nuclear Fusion experimental reactor.

Tsuneaki MINATO Tsuneaki Minato holds a Doctor in Engineering in Osaka University, Japan. He joined Mitsubishi Electric Corporation in 1983 and has been engaged in the design of magnetic coils of Nuclear Fusion experimental devices. He engages in the production design of the ITER TF coils since 2012.

Kazuo KUNO Master's degree holder from Kyoto University. Jointed Mitsubishi Electric Corporation in 1974. Have been working in the field of superconducting magnet, fusion devices. Now a project leader in Mitsubishi Electric for ITER TF Coils.