Development of advanced Nb_3Al superconductors for a fusion demo plant

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Abstract. Nb_3Al superconductor has inherently outstanding features of large critical current, high critical field and excellent strain tolerance in critical current performance. Japan Atomic Energy Research Institute (JAERI) developed the world's first large Nb_3Al coil, the Nb_3Al Insert, using jelly-roll processed Nb_3Al strands. This coil was successfully operated up to the nominal current of 46 kA at the nominal field of 13 T. The test results of the coil demonstrated that a Nb_3Al conductor is suitable to the application to high field, large magnets, such as Toroidal Field coils in a fusion reactor, which experience large electromagnetic force in the conductor. In parallel with this work, a Nb_3Al strand having high critical current at high field has been developed by National Institute of Material Science (NIMS). The technical issue of this strand in the application to a fusion magnet is stabilization against perturbation. This strand cannot include enough copper stabilizer, resulting in low stability, since it is heat-treated at much higher temperature than copper melting temperature. In order to find a solution to this issue, we performed an analytical study and it showed that the externally incorporated copper after the high temperature heat treatment is valid for stabilization when the electric conductance and heat transfer coefficient between the Nb_3Al strand and external copper are more than 10 MS/m and 10 kW/m^{2}K, respectively. It is expected that these values can be achieved by present conductor technologies. In conclusion, the possibility of development of a TF coil operated at high field around 16 T seems to be promised.

1. Introduction

A large current superconductor which can be operated at high magnetic field is required for fusion magnets. A15 superconductor, such as Nb_3Sn and Nb_3Al, is one of the candidates to achieve this requirement. A Nb_3Sn conductor was selected for the magnet system in ITER [1] since it was the most developed A15 superconductor in 1980s, and through the extensive R&D, Nb_3Sn conductor technology has been established.

Nb_3Al superconductor has inherently outstanding features of larger critical current, higher critical magnetic field [2] and excellent strain tolerance in critical current performance [3], as can be seen in Figure 1 [4], compared to Nb_3Sn. These features can provide a possibility to realize a fusion magnet that can be operated at around 16 T, higher than 13 T obtained by Nb_3Sn in ITER [1]. In addition, the superior strain tolerance of Nb_3Al can simplify the fabrication process of a Toroidal Field (TF) coil [5].

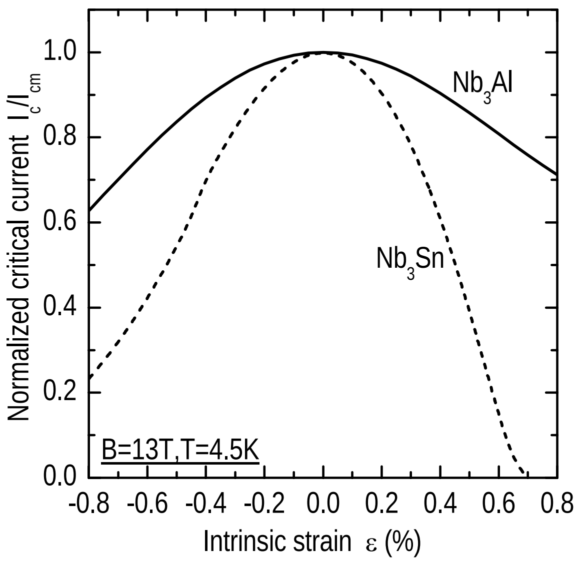

FIG. 1 Critical current dependence of Nb_3Al and Nb_3Sn on strain.

Based on this consideration, Japan Atomic Energy Research Institute (JAERI) has started the development of the Nb_3Al conductor from the middle of

1980s, aiming at its application to the TF coil of a fusion demo plant, which will preferably be operated at more than 16 T from economical acceptance point of view. As an intermediate achievement of this development, a Nb_3Al strand using a conventional jelly-roll method [6] has been developed [7], and a large-scale coil, named Nb_3Al Insert [8], has successfully been manufactured.

Since the superconducting performance of the jelly-roll processed strand was lower than the inherent level of Nb_3Al, further improvement was explored. Recently, the National Institute for Materials Science (NIMS) has successfully developed a Nb_3Al strand with a Rapid-Heating, Quenching and Transformation (RHQT) method [9], which can provide much higher superconducting performance than the conventional jelly-roll processed Nb_3Al strand. Technologies at JAERI and NIMS are now being combined to develop high performance Nb_3Al conductor using RHQT processed Nb_3Al strands, which is hereafter called as ‘advance Nb_3Al conductor’ for simplicity, for high performance fusion magnets which will be operated at around 16 T.

This paper gives the major achievements obtained in the development of the Nb_3Al Insert, and results of an analytical study to overcome a major technical issue in the application of the RHQT Nb_3Al strand to the conductor for fusion magnets.

2. Development of a large-scale Nb_3Al coil

The conductor of the fusion magnets generally requires sufficient amount of copper for stabilization against perturbation: perturbation drives part of conductor to a normal state and sufficient amount of copper helps the conductor return to superconducting state. Stoichiometric Nb_3Al having high critical magnetic field can be obtained by heat treatment at a very high temperature, more than 1800 °C, which is much higher than the melting temperature of copper, ≈1080 °C. The inclusion of sufficient copper in the strand, therefore, was almost impossible. As one of the solutions to this technical issue, JAERI has developed a jelly-roll processed Nb_3Al, which enables the generation of Nb_3Al with a practicable heat treatment at around 750 °C owing to a small diffusion distance for Nb_3Al formation. A mass-production technique has been established for this strand [10] and a 150-m conductor, shown in Figure 2, was fabricated. Table I summarizes major parameters of this conductor.

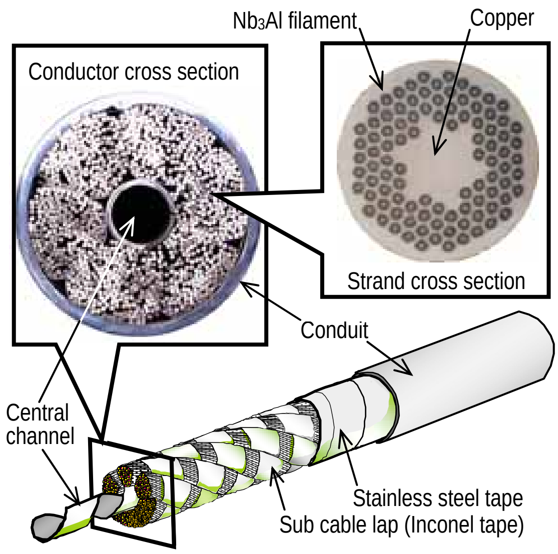

FIG. 2 The Nb_3Al conductor.

TABLE I
MAJOR PARAMETERS OF THE CONDUCTOR

Strand	
Diameter	0.81 mm
Critical current density	620 A/mm^2 (12T,4.2K)
Cu/Non Cu ratio	1.43
RRR of Cu	120
Surface	2 μm Cr plating
Conductor	
Number of strands	1152 (3×4×4×4×6)
Outer diameter	42.6 mm
Thickness of conduit	2 mm
Conduit material	Stainless steel
Central channel O.D.	12 mm
Central channel I. D.	10 mm
Void fraction	36% (cable space)

Using this conductor, the Nb_3Al Insert was manufactured, which is the world's first application of Nb_3Al to a large-scale magnet. The coil was tested in the bore of the ITER Central Solenoid (CS) Model Coil [11] as shown in Figure 3. Major parameters of the Nb_3Al Insert are listed in Table II.

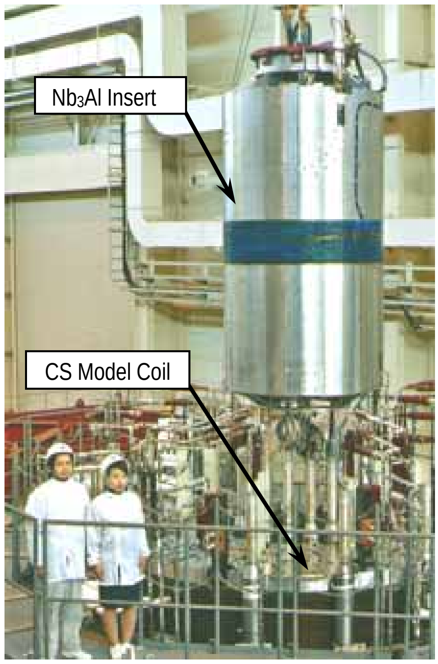

FIG. 3 The Nb_3Al Insert.

The test of the Nb_3Al Insert was performed in 2002 at JAERI. The rated field and current of 13 T and 46 kA, respectively, were successfully obtained. Furthermore, extended charge to 60 kA was carried out at 12.5 T. Figure 4 shows the achieved technologies of the Nb_3Al Insert with those of other superconducting coils constructed so far. The technology of the Nb_3Al coil comes to the same level as that of Nb_3Sn.

TABLE II
MAJOR PARAMETERS OF THE NB_3AL INSERT

Number of turns	20
Winding diameter	1.43 m
Outer diameter	1.56 m
Inner diameter	1.35 m
Height	2.80 m
Weight	7.8 ton
Nominal current	46 kA
Nominal field	13 T

One of the most important objectives of the experiment is to compare the conductor critical current to that of a single strand and to obtain precise estimate of a strain state of the conductor because the conductor critical current degrades due to a strain. One of the sources of the strain is the different thermal expansions between the strand and conduit. If there is unexpected degradation, the measured critical current is lower than that expected from the thermal strain alone. Therefore, the critical currents of the Nb_3Al Insert were measured in detail [12].

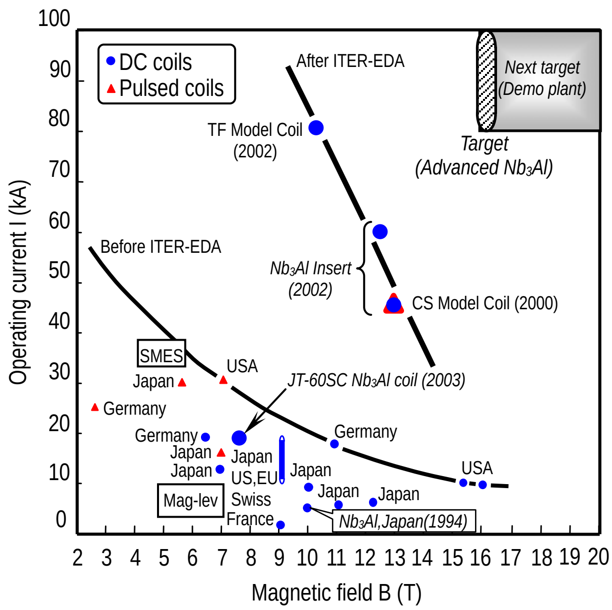

FIG. 4 Operating points of superconducting coils constructed so far and the target for the fusion demo plant.

Effective strain, defined by the following equation, is generally used to briefly figure out if there is an unexpected degradation in the critical current performance.

$$\varepsilon_{eff} = \varepsilon - \varepsilon_L \qquad (1)$$

Where ε_L denotes hoop strain arising from the global deformation of the coil during energization and ε is determined to give the best fitting between the measured critical current and the calculation [12, 13]. Figure 4 shows the evaluated effective strain of the Nb_3Al Insert conductor as a function of the electromagnetic force (coil current x maximum field). For comparison, Figure 5 also shows those of the Nb_3Sn

conductors, which were used in the CS Insert [14] and TF Insert [15] and are the same in size and current capacity as the Nb_3Al conductor. If there is no unexpected degradation in the critical current performance, it should be a constant, *i.e.*, thermal strain. In case of Nb_3Sn conductors the effective strains decrease as increase of the electromagnetic force. It means that the critical current performance of the Nb_3Sn conductor was degraded by the large electromagnetic force. In contrast, that of the Nb_3Al conductor is almost constant and no degradation appeared. This behavior can be explained by the higher stiffness and larger strain tolerance of Nb_3Al strand compared to those of Nb_3Sn. This result demonstrated that the Nb_3Al conductor is suitable to the application to large magnets, such as TF coils of a fusion reactor, which experience large electromagnetic force in the conductor. This conclusion is also supported by the success of the extended charge to 60 kA at 12.5 T, which is 25% larger in the electromagnetic force than that of the nominal operation.

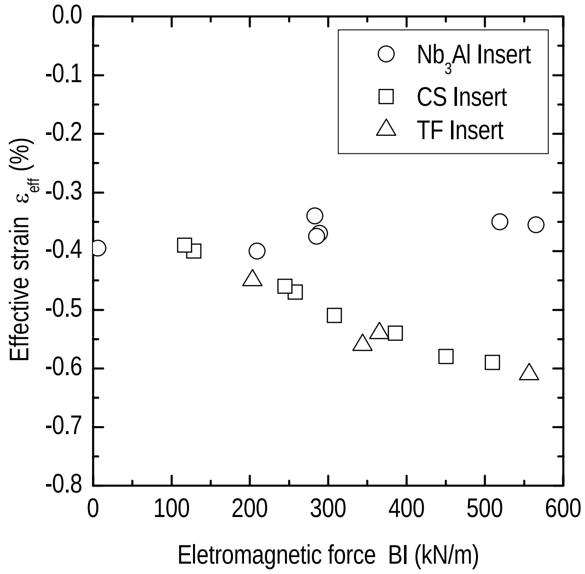

FIG. 5 Effective strain evaluated for the Nb_3Al Insert conductor. Those for the same scale Nb_3Sn conductors of the CS Insert and TF Insert are shown for comparison.

3. Development of advanced Nb_3Al conductor

The target of superconducting coil development for a fusion reactor next to ITER is a maximum magnetic field of more than 16 T with an operating current of more than 80 kA, as shown in Figure 4 [8]. However, the critical current density of the conventional jelly-roll processed Nb_3Al strand developed by JAERI is not sufficient at more than 16 T. In contrast, the critical current density and critical magnetic field of the RHQT Nb_3Al strand developed by NIMS are significantly higher than the conventional jelly-roll processed Nb_3Al strand, as shown in Figure 6. Therefore, JAERI and NIMS started the collaboration work to develop the advanced Nb_3Al conductor for the next fusion reactor. In this collaboration, NIMS performs strand development based on RHQT method and JAERI performs conductor technology development.

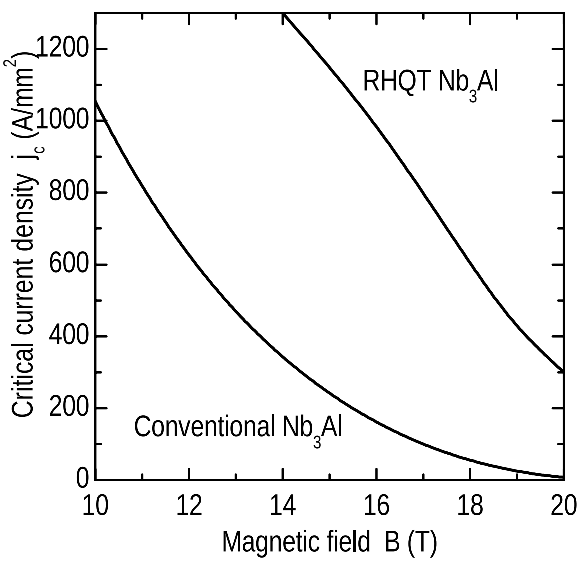

FIG. 6 Critical current density of the conventional jelly-roll processed Nb_3Al strand and RHQT Nb_3Al strand.

In the RHQT method, Nb_3Al strand is

rapidly ohmic-heated up to around 1900°C and quenched to generate supersaturated bcc-solid-solution ($Nb(Al)_{ss}$), as shown in Figure 7, followed by transformation annealing at around 770 °C to form Nb_3Al phase from bcc $Nb(Al)_{ss}$. Since the ohmic-heating temperature is far above the melting point of copper, the copper could not be included basically in the strand as a constituent element in this process. Therefore, sufficient stabilization of the conductor against disturbance cannot be performed, which is a major technical issue in this application. As one of the solutions to overcome this issue, a method to supplement enough copper before the transformation annealing has been proposed. In this proposal, a cable of the RHQT Nb_3Al strand surrounded by a cluster of copper wires is compressed in diameter and then transformation-annealed, as show in Figure 8, in order to obtain sufficiently good electrical and thermal contact between the Nb_3Al strand and external copper.

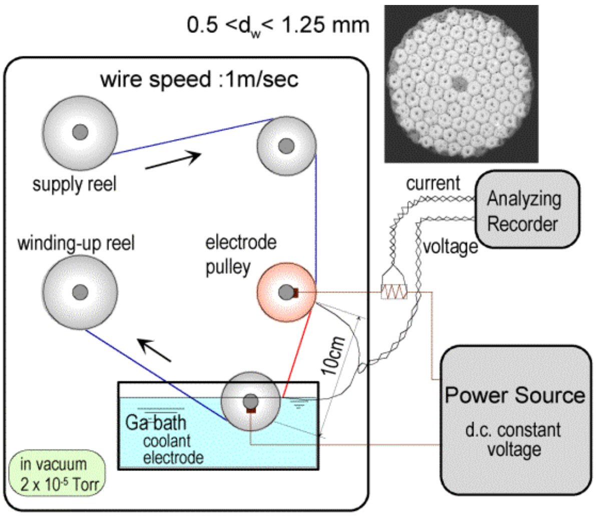

FIG. 7 Rapid-Heating and Quenching method.

The basic idea of the above solution is as follows. When part of the conductor becomes normal, the current in the Nb_3Al strand can be transferred to the external copper wires if the electric conductance is sufficiently small. Then a joule heating occurs in the copper wires as well as in the strand, which are cooled by the surrounding coolant and heat conduction in the axial direction, as can be seen in Figure 9. Recover to a superconducting state, therefore, depends on the speeds of the current transfer and cooling, *i.e.* degree of the electrical and thermal contact between the strand and external copper. A numerical analysis was performed to show that the external copper provides the stabilization and to estimate the required

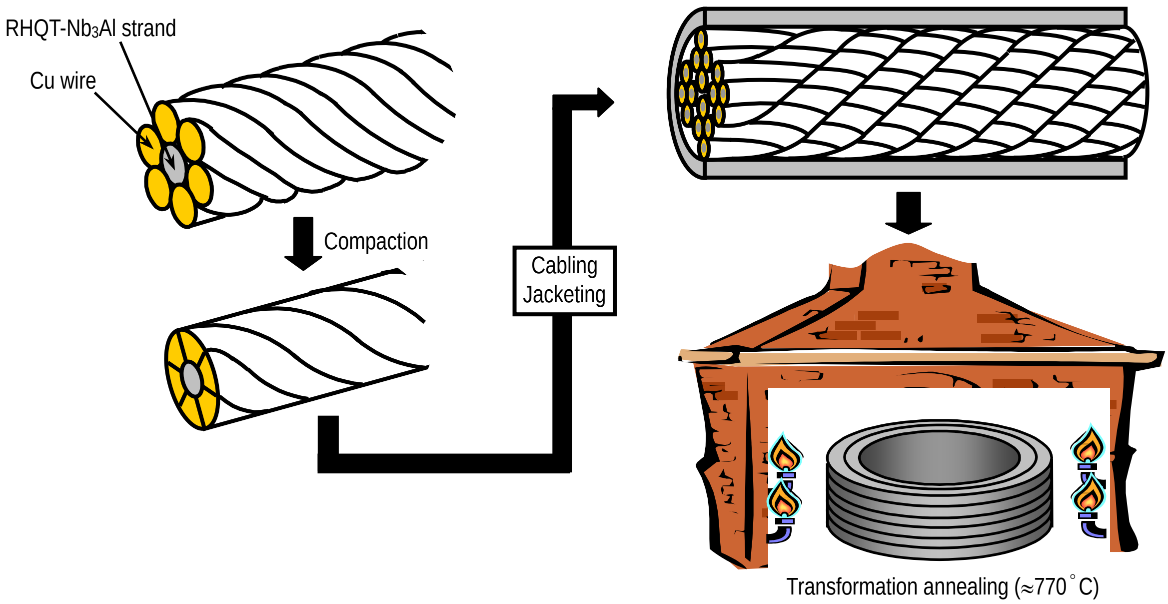

FIG. 8 An example of stabilization of RHQT Nb_3Al strand by using external copper wires.

parameters on the electrical and thermal contact. The analysis used one-dimensional fluid dynamics equation consisting of continuous, momentum and energy equations, and heat conduction equation in the cable [16] and a distributed circuit model for simulating current transfer (Figure 9).

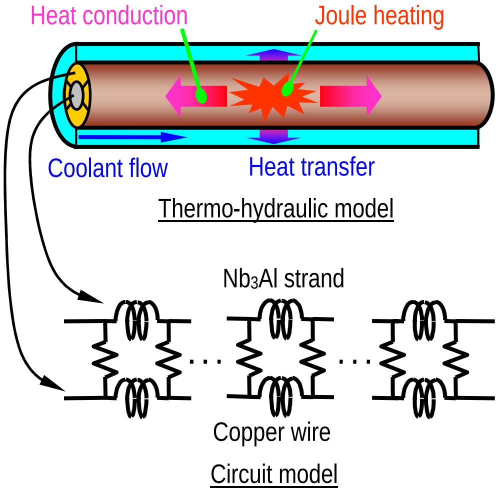

FIG. 9 Simulation model.

Some of the key parameters were measured in small experiments. Electric conductance between the RHQT Nb_3Al strand and external copper was measured by NIMS using the various samples, in which copper stabilizer was incorporated by 1) co-drawing with a copper tube, 2) cladding with a copper sheet, 3) ion-plating with copper and 4) subsequently electroplating [17]. The electric conductance was measured to be in the order of 10^6 – 10^{10} S/m. In our simulations, the conductance of 10^6 – 10^9 S/m was used, and conductance of more than 10^8 S/m does not give significant change in the stability as can be seen later. Thermal contact between the strand and external copper can be represented by heat transfer coefficient. K. Takahata et al. reported that the heat transfer coefficient between the cable and conduit is in order of 200 - 5000 W/m^{2}K [18], although their thermal contact is not as good as the proposed Nb_3Al conductor because there was no compaction in diameter. Our simulations were carried out for the heat transfer coefficient of 500 – 50000 W/m^{2}K, which may be pessimistic. The copper/non-copper ratio and current density of the conductor are also key parameters in the stability simulation. They were assumed to be almost the same as those of the ITER-TF conductor.

The simulation was performed by putting a heat in the center of the conductor over the length of 2 cm, with a perturbation period of 1 ms assuming a local wire motion in the conductor, and performance of the conductor was evaluated to see if it goes normal or return to a superconducting state. Figure 10 shows the calculated current and temperature of the Nb_3Al strand and external copper at the middle of the heated zone for the conductance and heat transfer coefficient between the Nb_3Al strand and external copper of 10 kW/m^{2}K and 10 MS/m, respectively. Result indicates that the current transfer from the Nb_3Al strand to copper immediately occurs (at $t \approx 0$) and

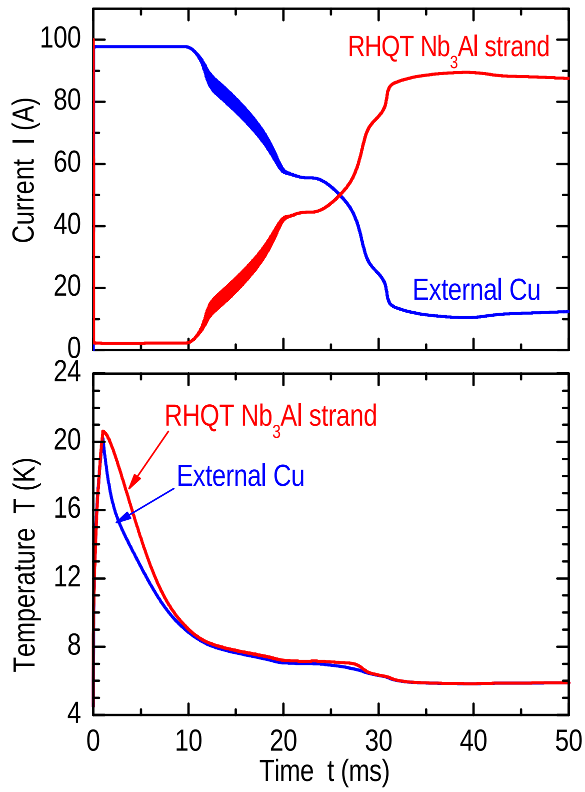

FIG. 10 Simulation results of the current and temperature. The conductance and heat transfer coefficient between the Nb_3Al and external copper is 10 MS/m and 10 kW/m^{2}K, respectively.

their temperatures go down quickly. As the strand temperature decrease, the current in the strand increases, but it does not completely return to the original value because the strand temperature is still a little higher than current sharing temperature as a result of temperature rise of coolant. However, this Joule heating is too small to make entire conductor normal, and will disappear when new fresh coolant is supplied.

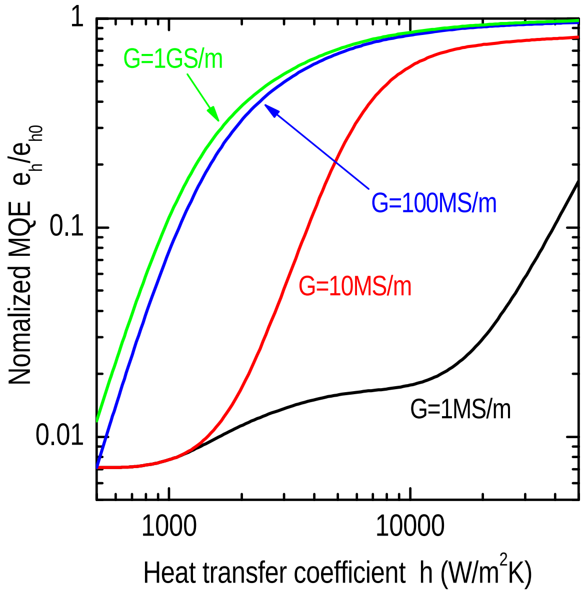

FIG.11 Simulation results of MQE.

Figure 11 shows the calculated minimum quench energy (MQE) normalized to 1.0 MJ/m^3, which is MQE of a single Nb_3Al strand having the same amount of copper in it. The MQE is almost identical at the conductance more than 100 MS/m. When the conductance is enough large, the current transfers from the Nb_3Al strand to the external copper very quickly, and entire stability is then limited by cooling capacity (*i.e.* heat transfer from the Nb_3Al strand to external copper). Accordingly, the dependence of the MQE on the electric conductance becomes small above certain value of the conductance.

The magnitude of the perturbation of 1.0 MJ/m^3 seems extremely higher than the actual disturbance during TF coil operation. However, the MQE of the externally stabilized cable can realize this value when the conductance and heat transfer coefficient between the Nb_3Al strand and external copper are more than 10 MS/m and 10 kW/m^{2}K, respectively. Since these conductance and heat transfer coefficient are expected to be achieved with the present technologies [17], the advanced Nb_3Al conductor is promising candidate for the superconductor in the fusion reactor, whose target operation areas are indicated in Figure 6.

4. Conclusion

The world's first large Nb_3Al coil, the Nb_3Al Insert, was successfully developed by JAERI and operated up to the nominal current of 46 kA at the nominal field of 13 T. The test results of the coil show that a Nb_3Al conductor is suitable for the application to high field, large magnets, such as TF coil of a fusion reactor, which experience large electromagnetic force in the conductor.

In addition, a Nb_3Al strand having high critical current at high field has been developed by NIMS. The technologies at JAERI and NIMS are being combined to develop a conductor using this high performance Nb_3Al strand. One of the technical issues in this application is stabilization since this strand cannot include sufficient copper because of its very high heat treatment temperature more than copper melting temperature. A solution to overcome this issue has been proposed, based on an idea to incorporate external copper before the transformation annealing. A simulation indicated that the externally incorporated copper can provide sufficient stabilization when the conductance and the heat transfer coefficient between the Nb_3Al strand and external copper are more than 10^7 S/m and 10 kW/m^{2}K, respectively. These values are expected to be obtained by the present technology. Therefore, the realization of a TF coil operating at a high magnetic field around 16 T seems to be promised.

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