Test of the NbAl Insert and ITER Central Solenoid Model Coil

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***Abstract*—The Central Solenoid Model Coil (CSMC) was designed and built by an ITER collaboration in 1993–2001. Three heavily instrumented Inserts have been also built for testing in the background field of the CSMC. The Nb_3Al Insert was designed and built by Japan to explore the feasibility of an alternative to Nb_3Sn superconductor for fusion magnets. The Nb_3Al Insert coil was tested in the CSMC Test Facility at the Japan Atomic Energy Research Institute, Naka, Japan in March–May 2002. It was the third Insert tested in this facility under this program. The Nb_3Al Insert coil was charged successfully without training in the background field of the CSMC to the design current of 46 kA at 13 T peak field and later was successfully charged up to 60 kA in 12.5 T field. This paper presents the test results overview.**

***Index Terms*—Cable-in-conduit conductors, losses, measurements, superconducting magnets.**

I. INTRODUCTION

THE NbAl Insert was built to study the performance of the NbAl CICC as a possible candidate for fusion magnets, particularly for the Toroidal Field (TF) system where requirements for low losses are not as severe as for the Central Solenoid (CS) and Poloidal (PF) magnets. The design of the NbAl Insert [1] is similar to the TF Insert tested earlier [2], which employs a thin wall conduit in the grooves of the supporting cylinder, which is also called mandrel.

The NbAl strand had 1.4 : 1 Cu : non-Cu ratio as opposed to 1.5 : 1 in the NbSn strands used in the previous tests [2], [3], but the cable configuration and Cr-plating were the same for all the cables. The total length of the CICC in the NbAl insert is about 92 m.

The attractive feature of the NbAl is significantly lower strain sensitivity than that of the NbSn strands, which is currently the strand of choice for the high field magnets for fusion. For example, a NbSn cable in stainless steel conduit will have only about 63% of the original strand's current capacity in 12 T and at 4.2 K at best, while a NbAl CICC in a steel conduit will have 77% of the strand's capacity, assuming -0.25% strain in the original strand and -0.7% strain in the strand in stainless steel conduit. This lower strain sensitivity of NbAl allows using stainless steel conduit with better efficiency than NbSn superconductor. Using stainless steel conduit reduces the conductor cost and makes fabrication easier and less risky than an alternative Incoloy or titanium conduits. Incoloy and titanium conduits do not degrade the superconducting properties as much as stainless steel due to a better match to the coefficients of thermal expansion, but they are more expensive and more difficult to process. A relatively high tolerance of the NbAl CICC to strain makes it possible to heat treat the conductor on a spool and then transfer the conductor into the winding pack, which is a version of a react-and-wind technology approach. The fabrication cost of the magnet, which allows such react-and-wind method, may be significantly lower than the cost of a magnet built by the baseline wind-react-transfer method.

The NbAl strands had a current density in 12 T and at 4.2 K comparable to the j_c of the average bronze route NbSn strands, but their T_c and B_c are lower than that of those for the NbSn strands.

Another disadvantage of NbAl results from the relatively immature process of strand fabrication, but hopefully this could be improved in the future. To achieve high current densities, the NbAl filaments are made very thick, 54 μm versus 3–4 μm for the NbSn strands in the NbSn CICC tested in ITER Model Coils. That generates hysteresis losses about 20 times higher than in comparable NbSn bronze route strands and 2–8 times higher losses than in an internal tin strand with much higher current density.

To demonstrate a low tolerance of the NbAl conductor to fabrication handling, the CICC was heat treated on a smaller diameter than the diameter of the final NbAl insert. This operation put a bending stress on the CICC. The strain in the conduit wall adjacent to the strands was about 0.4%, compressive at the outside radius of the Insert and tensile at the inner radius. The actual strain experienced by the strands is not readily known due

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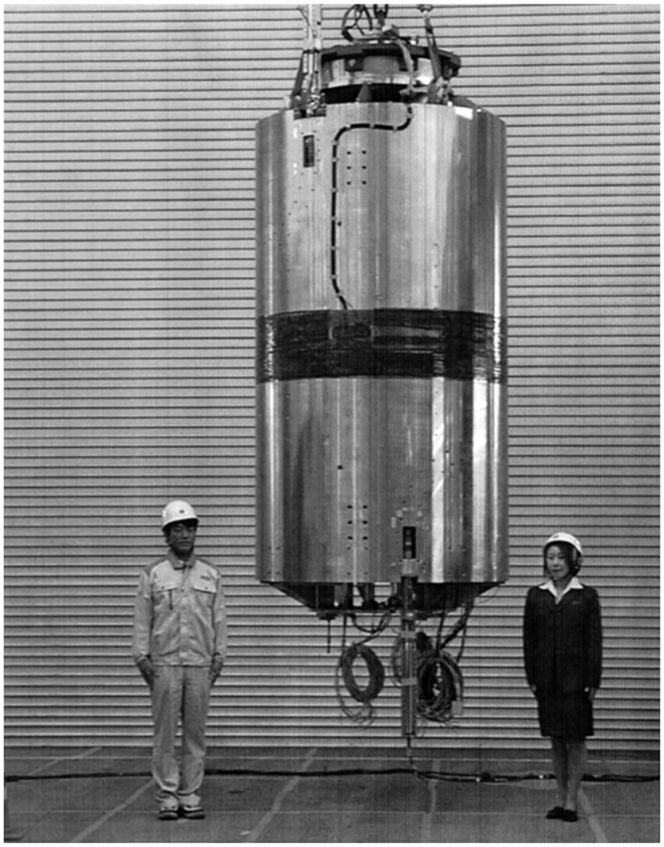

Fig. 1. NbAl Insert ready for installation into the CSMC Test facility.

to strand transposition in the cable and nonperfect bonding of the strands to the conduit, but obviously it cannot exceed these extremes. In a sense, this operation may help any strain sensitive CICC performance since the strands in the highest field will be in tension. This should enhance the CICC performance, providing the compressed strands in a lower field still have higher j_c properties and do not generate a weak link. This method [4], which promises to enhance the performance of the CICC, was not used on the previous NbSn Inserts due to the fear of damaging the strands during such handling. For the NbAl CICC fabrication the risk was accepted.

The winding pack was insulated with glass, impregnated with epoxy and cured. Cooling pipes were attached to the mandrel with epoxy only at the top and the bottom of the mandrel from the inside, above and below the winding pack. The heat transfer between the mandrel and the cooling tubes turned out to be very poor, therefore, all cooling to the NbAl insert was provided by the helium flow in the conductor. This cooling scheme caused significant temperature gradients between the conductor and the mandrel. The temperature sensors were installed on the conductor surface but anchored to the mandrel. This gave unreliable data and made determination of the temperature in the conductor difficult in most tests of this test campaign, especially at higher temperatures, like 15–16 K. However, we used the sensors to detect small temperature variations relative to some initial value after we found a reliable correlation between small relative changes as measured by the sensors on the conductor surface and the conductor temperature calculated from the inlet and outlet temperature sensors.

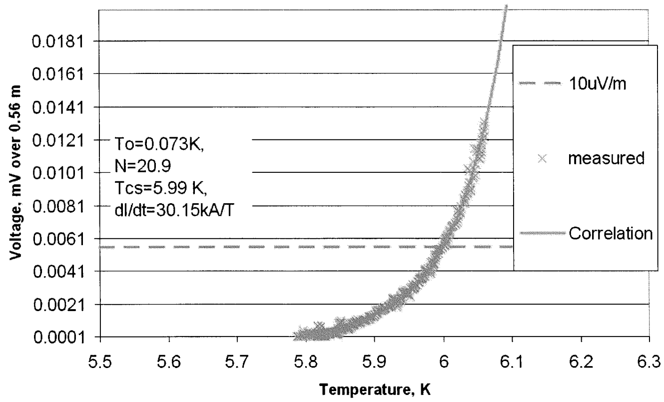

Fig. 2. Typical VTC and fitting curve at 46 kA, 12 T.

II. DC Performance of the NbAl Insert

A. NbAl Strand Properties

The strand for the NbAl Insert was fabricated by Sumitomo Co. and characterized by JAERI [5] and Durham University [6] with a good agreement between them. The correlations describing the NbAl strand properties were found for a wide range of parameters. Extensive studies of the strands showed a relatively low scatter of properties. The strands typically show critical current densities of about 620 A/mm^2 at 4.2 K, 12 T.

The N-value of the voltage-ampere characteristic (VAC) was also measured. The N-value is determined from the approximation of the voltage growth versus current as:

$$E = E_c \left(I/I_c\right)^N \tag{1}$$

or nearly equivalent to it relationship [2]:

$$E = E_c \exp\left(\frac{I - I_c}{I_o} + \frac{T - T_{cs}}{T_o}\right); \qquad N = \frac{I_c}{I_o} \tag{2}$$

where $I_c(T, B)$ is the critical current in the strand, I_o, T_o and N are the fitting parameters.

B. DC Measurements on the NbAl Insert and Comparison With Strand Properties

Total six measurements of the T_c and I_c were performed on the NbAl insert in the field range of 10–13 T and current between 0.6 kA to 46 kA. A typical voltage-temperature characteristic (VTC) is shown in Fig. 2, which also shows a fitting curve using equation (2). The fitting is very good in a wide range of the voltage.

This speculation and fitting the experimental data led to a conclusion that the best fit parameters correspond to the strands at the OD are at about -0.45% and the strands at the ID are at about -0.05% before energizing the Insert.

Fig. 3 shows good agreement between the experiment and the NbAl CICC model. At 20–30 kA the T_{cs} at inner and outer radii practically coincide.

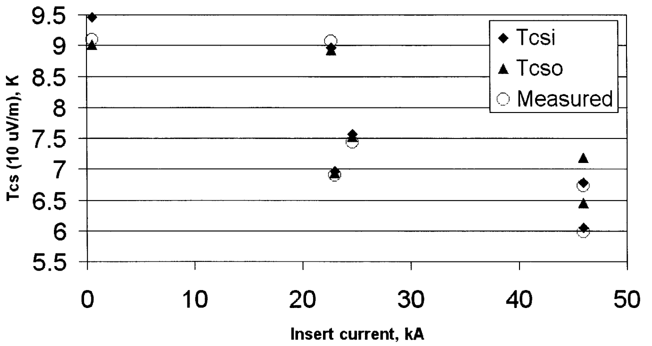

Fig. 3. Results of the T_{cs} measurements and fitting them to the NbAl strand correlations in the fields 10–13 T.

We also paid very close attention to the N-value in the NbAl CICC. Although the N-values on the NbAl strand are available for 4.2 K only, we assume that the N-value for the NbAl strands correlates with the I_c value, as it correlates well for many NbSn strands. That makes comparison between the strand and the CICC possible, despite the fact that the N-values on the CICC were measured at elevated temperatures.We noticed that if we assume that the strand did not have any degradation and the performance of the cable was defined by the strands at the Insert inner radius (in the maximum field), then this correlation predicted results that were too optimistic for low currents. We speculated that at low currents the weakest portion of the conductor cross section was not in the maximum field, but in the area of the most compressive strain. Since the magnetic field nonuniformity in the cable cross section was proportional to the transport current in the NbAl insert; at low currents the field nonuniformity is small. In these conditions, the strands at the OD of the Insert, which are under compressive strain due to fabrication procedure, as discussed before, will be the weak link rather than strands at the ID, which are in tension. In other words, the manufacturing step, which introduces a tensile strain on the strands in a high field region and a compressive strain on the strands in lower field, results in appearance of the normal zone in different places of the CICC cross section depending on the transport current and the background magnetic field. This is in sharp contrast to all previous NbSn Inserts, where the strands in the maximum field area were always the limiting factor of the CICC.

Fig. 4 shows comparison of the N-value measured in the NbAl Insert I_c and T_{cs} measurements versus the N-value measured on the strand [6]. Some N-values of recently measured ITER relevant NbSn conductors are also shown by open symbols, encircled in the dashed oval. They include results of the CS Insert [3], TF Insert [2], TF MC [7] and the CRPP subscale tests [8]. Arrow lines in Fig. 4 connecting two CRPP points indicate reduction of the N-value after 2000 cycles.

Several observations could be made from Fig. 4. First, the N-value of the NbAl CICC is quite close to the strand N-value. This is in sharp contrast to the NbSn CICC, which showed the N-value about half or less of the N-value measured in the strands. Second, related to the first one, is that the NbAl CICC N-value is significantly higher than that of the NbSn CICC, while strand N-values are much closer for these materials.

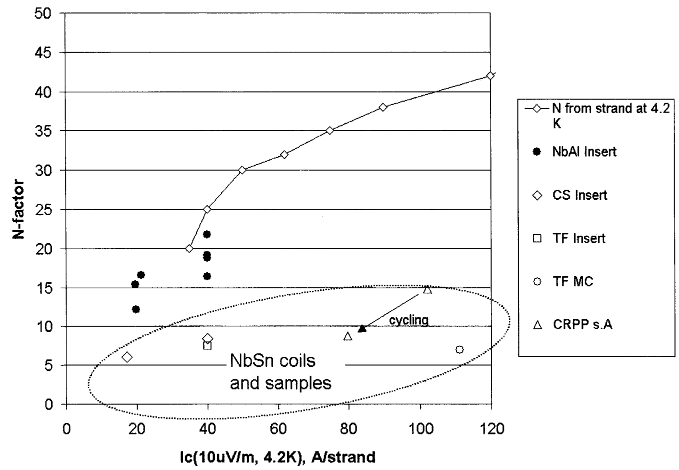

Fig. 4. Comparison of the N-value of the NbAl Insert to the strand N-value and to N-values recently measured in the ITER R&D tests.

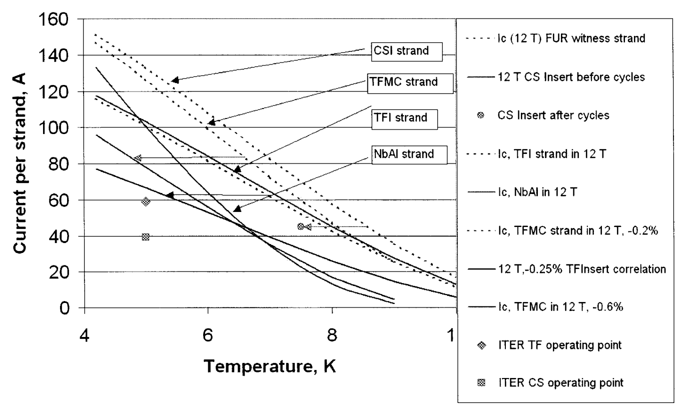

Fig. 5. Comparison of strand to conductor performance for CS, TF, NbAl Inserts, and the TFMC.

These two observations, in combination with the absence of degradation in the NbAl CICC, suggest several important speculations, which should be verified in the future R&D.

1) Since the NbAl cable is identical to the NbSn cables and the NbAl CICC shows no degradation, it suggests that the NbSn CICC degradation is not associated with the cable features (such as nonuniform current distribution in the cable) but with the change of intrinsic properties of the strands in the cable.

2) Since the major difference between the NbAl strand and NbSn strand at similar current is their sensitivity to strain, it is natural to assume that the degradation of the NbSn CICC and reduction of the N-value are strain related. It is not clear, however, how much of degradation comes from fabrication and how much from operation.

3) If strands are not degraded and damaged, the measured results of the I_c and N-values in the CICC are representative for the average properties of the strands in the cable if electrical field level is high enough to suppress other effects (like effects of the joints, etc.).

These assumptions narrow down the area of the future research directed to find out and possibly mitigate the reasons for the NbSn CICC degradation observed in recent experiments.

Fig. 5 compares performance of the magnets tested in the ITER Model Coil program. All data are brought to 12 T operation performance, using correlations obtained in the post-test analyses of all these tests [2], [3], [7]. The dashed lines show performance of the original strands used in the magnets and the horizontal arrow lines from these dashed lines to the solid lines represent the degradation of the CICC. The NbAl CICC did not experience any degradation; therefore the strand and the CICC performance coincide. The TFMC CICC performance is calculated assuming -0.7% compression, in this sense the TFMC degradation results entirely from the natural mismatch between the strand and the stainless steel conduit and is expected in contrast to the other NbSn magnets.

The ITER operating points correspond to thinner strands with higher j_c, but the I_c requirement in 12 T remains very close to the requirements of the I_c of the grade 2 strands used in the Model Coil program (550 A/m^2). That makes the comparison of the tested conductors to the new ITER requirements sensible.

It is seen that in terms of T_{cs} margin, the NbAl CICC is significantly better than the TFMC and TF Insert at the ITER TF operating current, but lower than the CS Insert CICC despite degradation of the latter. In other words the NbAl strand has a very good predictability of the CICC performance while the best NbSn materials in low CTE conduit exceed the performance of the NbAl strands even after degradation of the NbSn.

III. Effect of Cycling and Quenches on the DC Properties

The NbAl Insert was exposed to a cycling load for 1000 cycles in 13 T, 0-to-46 kA and also experiences several quenches, the most intensive of which raised the temperature in the hot spot up to 160 K. The change of the T_{cs} in the NbAl Insert was less than 20 mK, which is well within the measurements error.

IV. Joint Performance

The joints of the NbAl Insert showed a very reliable performance. The resistance was about 1 nOhm.

V. Stability and Normal Zone Propagation

The stability of the NbAl Insert was measured using an inductive heater on the conduit. The measurements showed that most of the available enthalpy of helium is utilized, which shows that the design of the NbAl conductor operates in a well-cooled regime, similar to all tested Inserts.

The normal zone propagation was studied up to 4.5 s delay between the normal zone initiation and the energy dump. The maximum temperature of the conductor was estimated to be 160 K. Since no noticeable change in CICC properties was observed, this result verifies that the design criteria of 150 K maximum hot spot temperature is an acceptable limit, which should not affect performance of the NbAl CICC.

VI. AC Losses

The AC losses were measured using compensated pick up coils. Preliminary data showed that the hysteresis losses correspond to expectation from the strand measurements and the coupling losses reduced after several tens of charges and remained unchanged, qualitatively similar to the CS Insert behavior, but the amount of the coupling losses was about 2–3 times higher than in the CSx Insert.

VII. Conclusion

The NbAl Insert reached all design objectives. It reached 46 kA in 13 T and later 60 kA in 12.5 T with no training, and it showed low intensity of the acoustic emission signals.

The NbAl Insert showed no degradation of the strand properties and the N-value. The tests demonstrated industrial capabilities to produce a large strand lot (1 t) with high consistency and showed that the NbAl CICC can be developed into an attractive candidate for fusion magnets.

The NbAl Insert tests gave very valuable data not only about performance of the NbAl itself, but also for the NbSn Inserts behavior interpretation.

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