Review of Scientific Results Obtained During Production of ITER TF and PF Conductors in Russia

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***Abstract*—Russian Scientific R&D Cable Institute was obliged to produce and deliver 20% TF conductors and 20% PF cables for ITER magnet system. The task has been completed by the October 2015. Special technological complex has been accomplished to produce PF cables for both the Russian Federation (RF) and European parts and TF conductors for RF part. This work was the great scientific and technological challenge in development of tricky technologies in many aspects and directions. It also permitted to get many interesting scientific results. Developments of manufacturing processes were accompanied by extensive scientific studies directed to improve technologies and to find out the reasons of changes of properties of cables and conductors during manufacturing and testing. In this paper we present the extended review and summary of scientific results obtained during production time which allowed deeper understanding and improving manufacturing process and quality of TF and PF conductors for ITER magnet system. These results could be useful for suppliers of cables and conductors of superconducting magnets using ITER – like technologies.**

***Index Terms* — Cable-in-conduit conductors (CICC),cabling and jacketing, superconductors properties, ITER.**

I. Introduction

RUSSIAN Scientific Research and Development Cable Institute (known by Russian abbreviation as VNIIKP) has a long story of its presence in the ITER Project. We participated in early Research and Development (R&D) works then in Engineering Design Activity (EDA) stage [1-4]. Since 2007 up to 2009 the full technological complex has been accomplished to produce cables for poloidal field (PF) magnets for both the Russian Federation (RF) and European parts and conductors for toroidal field magnets (TF) for RF part [5]. This work was the great challenge in development of tricky technologies in many aspects and directions. Several technologies including electrochemical ones, cabling and jacketing were developed and certified in full accordance with ITER Procurement Arrangements (PA) [6] – [8]. All tasks assigned to us for production and delivery have been completed by October 2015.

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This work was supported by ITER-Center (RF ITER Domestic Agency – RF-DA *(All authors contributed equally to this work) (Corresponding author: V.S. Vysotsky, e-mail: vysotsky@ieee.org)*

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Very important parts of our ITER works were several R&D studies directed to improve technology or to find out the reasons of changes of properties of cables and conductors during manufacturing and testing.

The TF (and other cables also) are rotate and untwist during insertion into conduit. Increase of twist pitch will lead to increase of AC losses in a conductor. Our study of rotation and untwisting of TF cables during insertions into jackets allowed to develop the model describing the rotation process and to suggest the device which keeps untwisting within demanded levels.

Analyses of mandatory SULTAN high field electromagnetic (EM) tests of PF and TF conductors from Russia confirmed good quality and adequacy of manufacturing processes. The reason of this behavior is not known yet. Micrographic studies of Nb_3Sn strands before and after SULTAN tests permitted us to suggest qualitative explanations the reasons of stability of RF TF conductors' behavior during multiple electromagnetic and thermal cycling.

Statistical studies of Residual Resistance Ratio (RRR) of Nb_3Sn and NbTi strands permitted to track the RRR degradation during manufacturing processes and SULTAN tests. The optimal heat treatment process for Nb_3Sn conductors has been confirmed after RRR statistical study.

The hydraulic performance has been measured in the short samples of TF conductor. By using the parameters obtained it is possible to predict hydraulic performance of helium flow in a conductor at any temperature.

In this paper we present the review of our scientific studies that could be useful for suppliers of cables and conductors of superconducting magnets using ITER – like technologies.

II. Rotation and Untwisting of Cables During Insertion

During manufacturing of CICC for ITER the twist pitch elongation due to cable rotation during insertion was found by many suppliers [9]. The cable twist pitch elongation can lead to additional AC losses therefore this phenomenon became the subject of studies by different manufacturers, and also led to attempts to describe it by the mathematical models predicting an elongation of twist pitch depending on the pulling parameters [10]. It should be noted that number of cable head rotations varies considerably depending on the supplier.

A cable rotation model developed in VNIIKP is based on the fact that when an axial load is applied to a body, having a helical anisotropy (e.g., a cable) there is a torque leading to untwisting, at its point end. On the basis of the model the equations were derived for the number of rotations (1) and the twist pitch (2) along the length of the cable:

$$\theta(A)=\left(\frac{2A}{\frac{1}{A}\cdot\sqrt{r_0{}^2+r_{sp}{}^2\cdot(A^2-1)}+r_{sp}}\sqrt{\frac{L_0{}^2}{h_0{}^2A^4}-\frac{1}{4\pi^2}+\frac{1}{h_0}}\right)2\pi \qquad (1)$$

$$h(A,\theta(A))=\frac{A^2\cdot 2\pi z}{2\pi z-\theta(A)h_0} \qquad (2)$$

here: θ – is rotation number of cable head, r_0 and r_{sp} are initial cable radius and spiral radius correspondingly, L_0 – subcable length, h_0 – initial twist pitch, z – cable length

Both equations include the pattern coefficient A that takes into account the mechanical and structural characteristics of the cable. Parameter *A* has to be determined experimentally on the short model sample of each cable before the estimation of twist pitch values *(P_{twist})* after insertion. To determine the parameter A we carried out the tensile test of the short sample of RF TF cable together with our colleagues from "Hitachi-Cable" [11]. As the result of this experiment the cable twist pitch elongation (Fig.1) and number of cable head rotations versus pulling force (Fig.2) have been obtained. Additionally, the dependence of the cable rotation number on its length was also obtained for different values of tensile force.

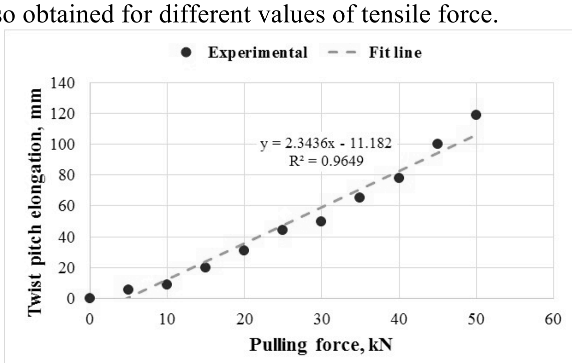

Fig. 1 Twist pitch of the cable depending on the applied force.

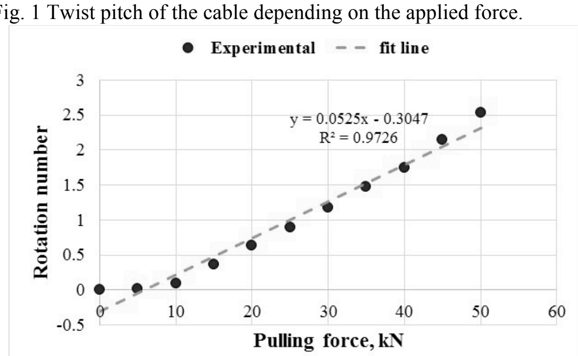

Fig. 2 Number of rotation of the cable depending on the applied force.

Based on the experimental data, we determined the parameter A as a function of the point end rotation number, and also the parameter *A* dependence on the cable length for different values of tensile force *F*:

$$A(F,z)=(1.565\cdot10^{-5}\cdot F-1.451\cdot10^{-4})\cdot z+0{,}999 \qquad (3)$$

Measurements of pulling force and number of rotations of a head have being carrying out during manufacture of every CICC unit length. We also had the opportunity to measure directly the twist pitch along the entire length at the cable with the conduit removed after breaking the pulling rope [12]. The data from both experiments allowed us to compare the calculated dependence obtained using the model with actual measurements of twist pitch. The results of measurement are shown in Fig. 3 and Fig. 4. One can see quite good coincidence of the experimental data and calculations.

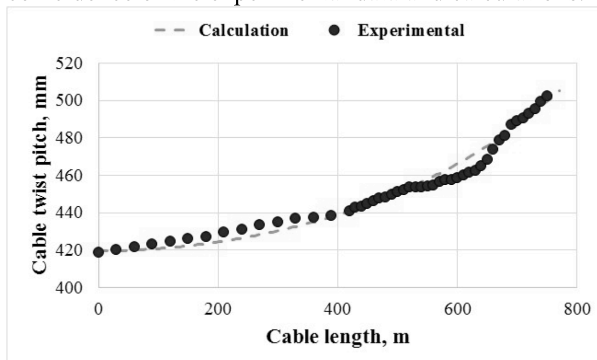

Fig. 3 The results of measurements and calculation of cable twist pitch during insertion.

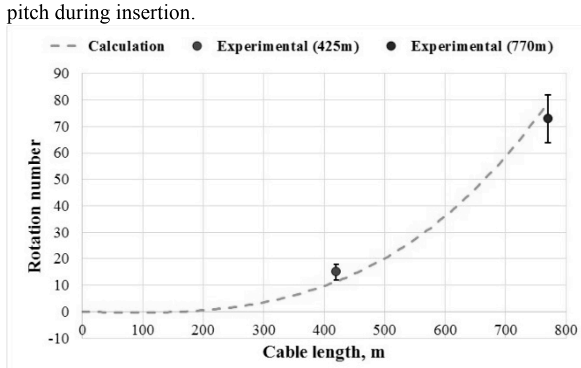

Fig. 4 The results of measurements and calculation of cable rotation number during insertion.

Based on these studies two methods were proposed for compensation of cable untwisting during insertion:

- a cable twisting with variable pitch, satisfying to the equation (4);

$$h_{var}=2h_0-h(z) \qquad (4)$$

here: h_{var} – is the cable twist pitch, h_0 – ITER required twist pitch, *h(z)* – the cable twist pitch determined from (2).

- to use a unit that prevents rotation of the cable (Fig. 5). The unit should produce the torque of the same magnitude but in opposite direction. We used the same cable, but twisted in the opposite direction (left twist while ITER cables should have right twist). The anti-rotation unit was tested with the experimental 320 m cable (Fig. 5). The comparison of difference in twist pitches for 10 m point end of the experimental cable both before and after insertion (Fig. 6) shows practically no elongation of twist pitch.

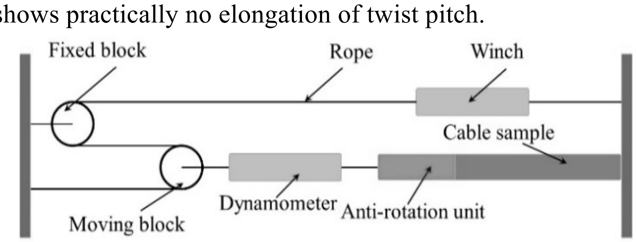

Fig. 5 The scheme of experimental insertion with the anti-rotation unit.

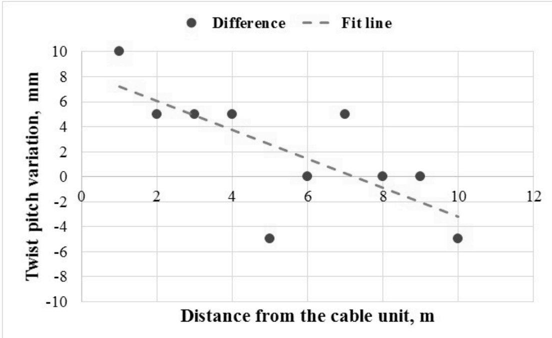

Fig. 6 The difference of twist pitches before and after insertion with anti-rotation unit on the point end of the experimental cable.

III. Strand Defects Induced in the Russian TF Conductor during the "Sultan" Test

In the ITER superconducting magnet system strong cycling Lorentz forces are induced. These forces lead to the movement of the strands within the CICC and provide conditions when especially strongly curved strands can develop tensile and bending strains on their outer surfaces. In turn that can cause filament fracture at quite high, localized densities. There are several suppliers which produce TF conductors for the ITER. Testing of short samples of full-size ITER TF CICC in the SULTAN have mostly shown that significant degradation of the current sharing temperature T_{cs} takes place during multiple electromagnetic cycling [13, 14]. Considering the value of the T_{cs} drop, RF conductors demonstrate very good stability during cycling among other ITER conductors.

It should be noted that the important differences exist between the strands used by different suppliers [15] with regard to their susceptibility to filament cracking under strain applied. So the characterization of the strand defects allows estimating the filament cracking contribution into T_{cs} degradation during SULTAN testing. Also, the technology of conductor manufacturing might differ among the supplier in spite of the fact that they produce conductors fulfilling the common ITER specification [6].

We have studied filament cracking in strands extracted from our TFRF3 [16] conductor sample after full size SULTAN testing [17] and compared our finding with the same results obtained for TFEU5 conductor [18]. Both conductors were manufactured on the base of bronze route strands. However RF strands has specific layout [19] with well distributed filaments in cross section (Fig.7a, b).

We observed cracking of individual filaments in strands situated in High Field Zone (HFZ) when testing of the conductor, but did not observe total destruction of the filaments in the sub-elements. Besides cracks at the angle between 90 ° and 45° to filament axis which are typical for all Nb_3Sn strands (Fig.8 a, b), the other two types of cracks (semi-cracks and longitudinal cracks) can be attributed to a “fillet” shape of filaments formed by stacking of pair Nb rods (Fig.8 c, d).

Among other observations it may be noted that non-uniform distribution of voids in bronze matrix (in particular, clustering of large voids) can lead to additional filament damage because most of filament cracks are void-induced (Fig.9).

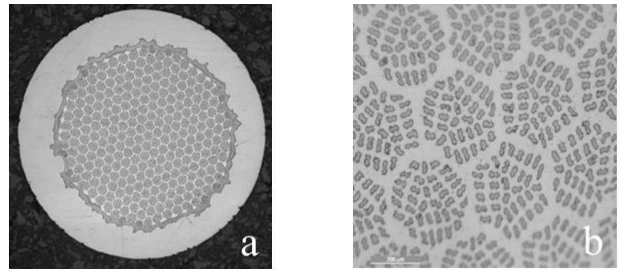

Fig.7. a - Cross section of RF bronze strand; b - Fragment showing the strand filament shape

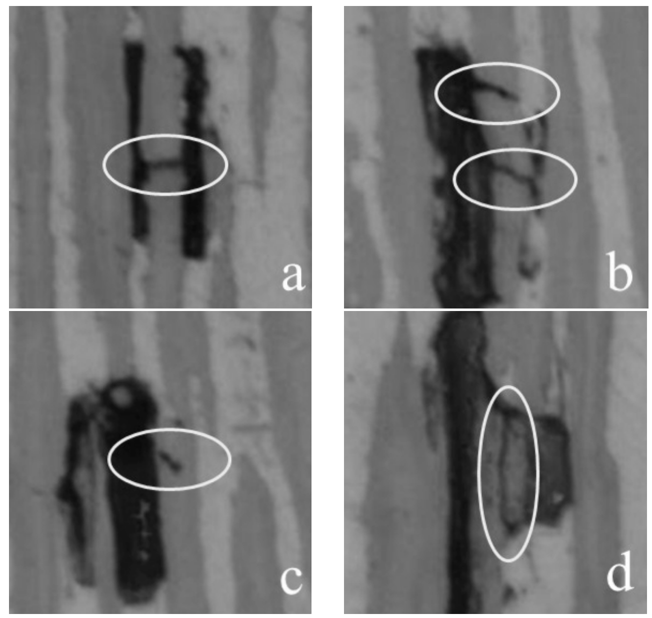

Fig. 8. a - crack perpendicular to filament axis; b - crack crosses the filament at the angle 45o to filament axis; c - crack extends over a half of filament width; d - Longitudinal crack of superconducting filaments

As for the effect of strand position in conductor cross-section, we have found a difference of cracks number (about two times) in strands situated nearby the jacket or in the center of a petal and also between the strands extracted from HFZ and LFZ (Fig. 10a). One can see that in the strands taken from LFZ, no defects have been detected (Fig. 10b); it indirectly indicates that thermal cycling does not affect the formation of defects.

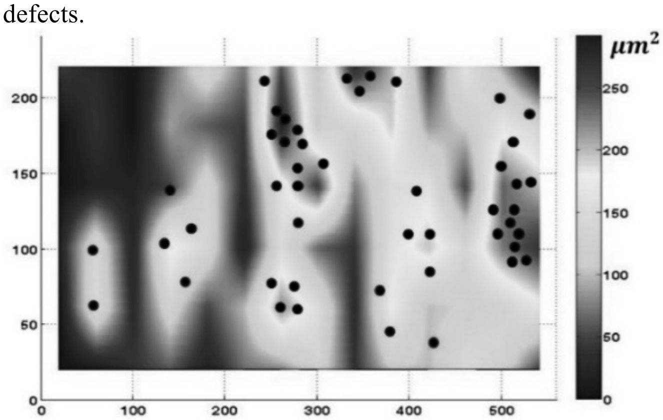

Fig. 9. Cracks positions against void area in bronze matrix. Black points indicate crack locations; the left bar shows the intensity of local void area.

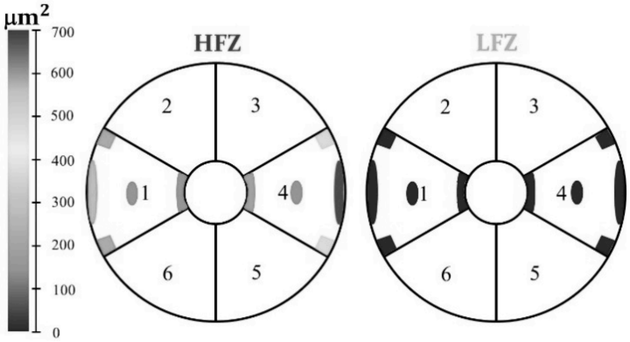

Fig. 10. Number of defects in strands taken from different positions in the cross section of theTFRF3 conductor

For comparison of our results with the results for TFEU5 we used 5-levels scale (cracks/mm2 of filament area) suggested in [18]. The diagram in Fig.11 presents cracks distribution in the samples taken from TFRF3 near the jacket in HFZ and cracks distribution in TFEU5. It seems that the strands in TFRF3 are less damaged; even in highly loaded samples there are no defects corresponding to 4 and 5 levels (> 2000 cracks/mm2) while in strands extracted from TFEU5 [18] these levels amount to 17% of total cracking.

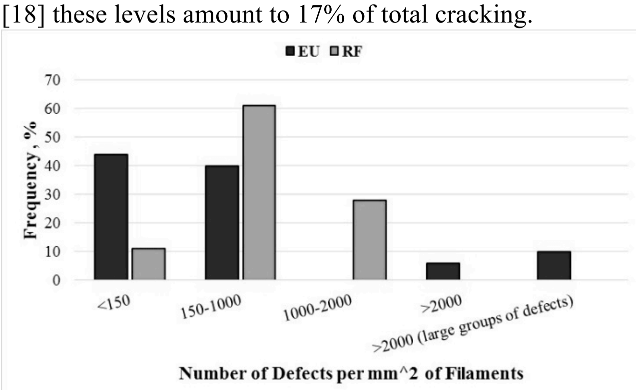

Fig.11. Number of defects per unit length of the superconducting filament in RF and EU conductors after the «SULTAN» test.

Based on these results we can conclude that well distributed Nb_3Sn bronze strands (with higher number of sub-elements) seem suit more for CICC manufacture due to their resistance against bending. The question is: could the stability of RF conductor be fully attributed to the good strand layout or differences in conductor technology also contribute to this phenomenon?

Our suggestion is that combination of several factors:
- very dense cable due to use of special roller compacters [8];
- rough Cr coated surface [18];
- good strand layout in RF TF strands;

could work altogether and lead to high stability of RF TF conductors.

Manufacture of TF conductor (Cr plating, cabling and jacketing) in the VNIIKP with the strands of different origin and following testing of CICC could answer this question.

IV. RRR Evolution during CICC Manufacturing and after SULTAN Test

The requirement for RRR ≥ 100 is included in the ITER technical specifications for the Nb_3Sn and NbTi strands used in the TF and PF conductors [6]. It is necessary to provide stability of superconductors during operation and have enough low resistive paths in case of quench.

We performed the extensive statistical investigations of RRR evolution both for the Nb_3Sn and NbTi strands [20, 21]. Our aim was to find out if conductors keep the required level of RRR after manufacture and testing of the CICCs. The results after SULTAN tests were obtained by measurements of strands extracted from the lengths corresponding to both HFZ and LFZ of PFEU1 conductor sample and TFRF3 conductor sample, which was heat treated by Cycle B. The average RRR at different stages of investigation are presented in Tables I and II. In general, RRR of both strands decreases during manufacture of conductors. The RRR reduction is mostly associated with the bending due to deformation on the guide rollers of the electrochemical plating facilities and strands deformation in cables during compaction of conductors (Fig.12).

TABLE I.
RRR of NbTi strand

Stage	Average RRR
Bare strand as-received	139
Ni-plated strand	130
Strand from compacted PF conductor	116
Strand from LFZ at SULTAN	116
Strand from HFZ at SULTAN	117

TABLE II.
RRR of Nb_3Sn strand

Stage	Average RRR
Bare strand as-received	208
Cr-plated strand	169
Strand from compacted TF conductor	145
Cr-plated strand heat treated by Cycle A	110
Cr-plated strand heat treated by Cycle B	138
Strand from LFZ at SULTAN	120
Strand from HFZ at SULTAN (near spiral and jacket)	106

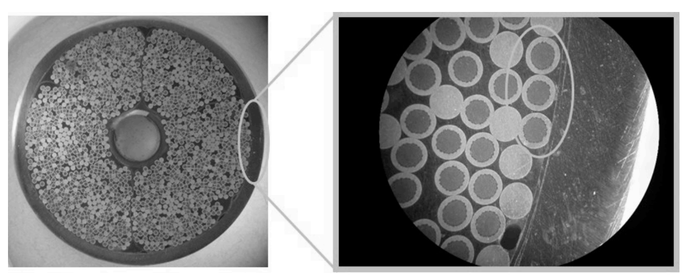

Fig.12. Deformation of strands as a result of a cable compaction

Fortunately, the average RRR of strands extracted from both SULTAN samples keeps well above 100 for both TF and PF conductors. However there are some differences in conductors RRR after test at SULTAN. PF conductor based on NbTi strands seems insensitive to electromagnetic cycling and its average RRR remains at the level of compacted conductor (Table I). The average RRR of TF conductor decreases, especially in Nb_3Sn strands located near spiral and jacket in the length corresponding to HFZ (Table II). There is about 34% of strands having the RRR values less than 100 (Fig.13).

Because average value of CICC remains above 100 over the conductor, that is enough for stability and protection of a magnet.

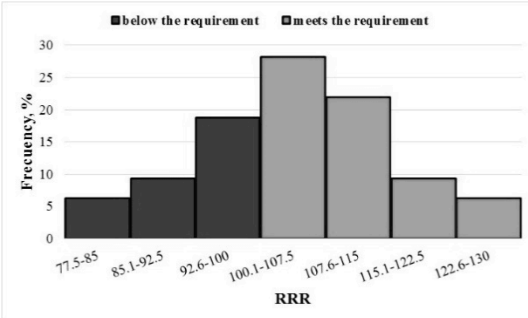

Fig. 13. Histogram of RRR distribution for the strands taken from HFZ of TFRF3 conductor sample.

We also performed the statistical study of the Nb_3Sn samples heat treated both by Cycle A (200 hours at 650 ^{0}C) and Cycle B (100 hours at 650 ^{0}C) and revealed that about 18% of strands did not fulfil the requirement right after heat treatment of Cycle A (Fig.4) while all samples heat treated by Cycle B had RRR above 100 (Fig.15).

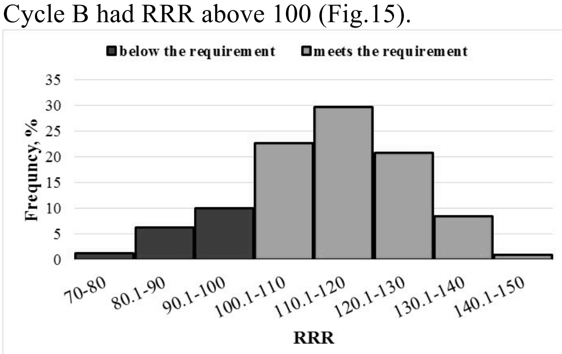

Fig. 14. Histogram of RRR distribution for the Nb_3Sn samples heat treated by Cycle A (200 hours at 650 ^{0}C).

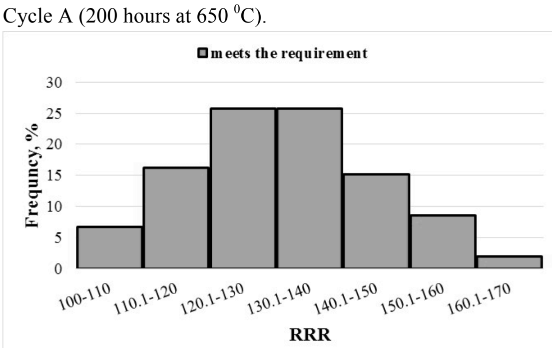

Fig. 15. Histogram of RRR distribution for the Nb3Sn samples heat treated by Cycle B (100 hours at 650 ^{0}C).

Taking into account the RRR drop after SULTAN test, we calculated that in case of using of Cycle A the average RRR of TF conductor will be less than 100 and amount to about 90. These investigations confirm that use of the Cycle B heat treatment was a correct decision.

V. ITER TF CONDUCTOR HYDRAULIC RESISTANCE

The hydraulic resistance is one of the main TF CICC's parameter to provide sufficient cool down and stable work of the magnet system during operation. The CICC is cooled down with liquid helium flow, which splits between central cooling spiral and petals void fraction.

Every conductor unit length (UL) is undergone final acceptance tests, which include pressure drop measurements. The pressure drop test is performed with dry nitrogen gas at room temperature and is aimed to determine conductor hydraulic performances by measuring gas mass flow rate at different pressure drops.

During our ITER production we performed the special model study and developed a model developed in accordance with the theory of turbulent self-similarity in order to estimate the hydraulic performances of TF CICC at any temperature basing on the results of final acceptance test [22].

The study was carried out to develop two-flow model to describe hydrodynamic properties of TF ITER CICC more precisely. Most difficult part was to determine equivalent hydraulic diameter and friction factor for both the spiral and porous cable by a calculation. An experiment involving VNIIKP, National Research Center (NRC) Kurchatov Institute and RF-DA has been performed in order to obtain those values.

For this experiment a short 10 m conductor sample has been manufactured. The sample was very similar to an ordinary TF conductor except the fact that the central cooling spiral had been replaced by a continuous copper tube of the same size OD×ID 10×8 mm. By plugging or unplugging the copper tube we could determine hydraulic performances of the whole experimental sample cross-section or cable petal area only (Fig. 16).

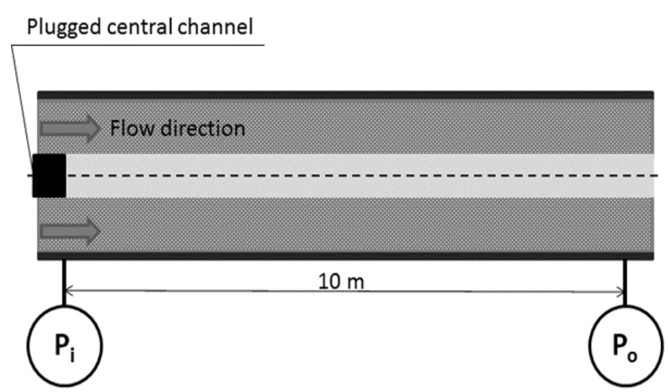

Fig. 16. Experimental sample overview. P_i and P_o are inlet and outlet pressure correspondingly.

Once the experiment results have been processed we have got a set of parameters for both the cable and the central channel were determined and that let us to cross-check the proposed data with some experimental results. The results of 100 m TF Qualification conductor test were used for that. As we know the total mass flow through the conductor – m_t, consists of mass flow rate through the cable – m_2 and through the central channel – m_1.

Values m_1 and m_2 have been calculated for 100m cable using values of hydraulic performances obtained in our experiment described above. According to our calculation 55% of the flow runs through the central spiral and 45% through the cable. Then m_1 and m_2 were compared to values of m_t, which was obtained experimentally. The results showed a very good match as show in Fig. 17.

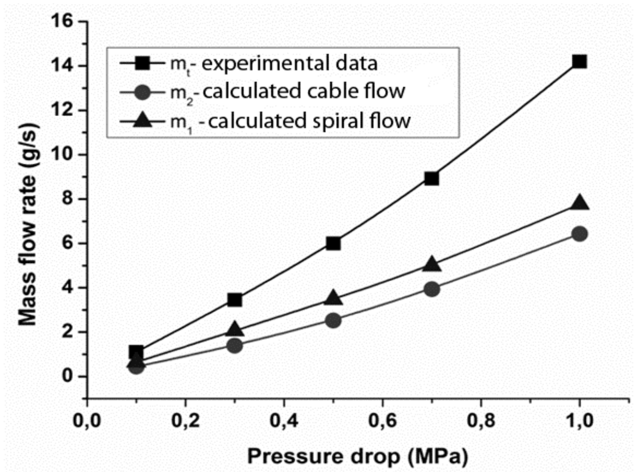

Fig. 17. 100 m conductor test experimental results - ■; proceeded in accordance with (7) mass flow rate through 100 m cable - ● and through central channel - ▲.

Eventually we achieved the goal. Two parallel flows model has been developed to estimate hydraulic performances of TF conductor at different temperatures. The tests were provided with nitrogen gas but using the data and calculation provided in [22] it is possible to recalculate the data for helium.

In the result of provided experiment we have got a value of cable equivalent hydraulic diameter and a formula to calculate the friction factor. It helped us to find out hydraulic performances of the central spiral. Using the parameters obtained it is possible to predict hydraulic performances of conductor for helium flow at any temperature.

VI. Conclusion

During *"A long and winding road"* (words of A. Devred at final Conductor meeting Sept. 2015) to produce ITER PF and TF conductors many scientific studies were performed along with technologies development and production. These studies permitted to improve technologies (studying the rotating and untwisting of a cable); to understand behavior of conductors after EM tests (studying the strand microstructure); to select proper heat treatment (statistical studying the RRR) or to predict hydraulic performance of conductors at helium flow (developing the method of calculation of gas flow).

Thus, ITER works stimulated many scientific developments that will be useful for future similar developments, especially if CICC technology will be used.

The results presented in this review are not complete; for example, many works on strand characterization [23, 24] or AC loss study in CICC before and after cycling load [25] and many others are only mentioned here as references, just due to limitation of space. Anyway, all these studies were performed being inspired by ITER.

We hope that this review and the references attached will be useful for future projects, especially if CICC technology will be used.

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