Research and Development for the ITER Toroidal Field Coils

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Abstract. The ITER Toroidal Field (TF) coils are made up of a winding pack enclosed in a case. In the central region the noses of the coils are wedge shaped and fit together to form a circular vault. On the outside an intercoil support structure joins the coil above and below the equator. The goal of the ITER project L2 is to verify the design principles, design procedures, design criteria, operating margins, analysis methods and manufacturing process, including Quality Assurance (QA) capable of application to the ITER TF coils. The project is divided into two subprojects: TF Model Coil (TFMC) construction and testing and TF coil case fabrication demonstration. The conceptual design of the ITER TFMC has been carried out by the ITER EU HT, the engineering design and construction by European Industries. The testing of the TFMC is foreseen in the TOSKA facility at FZK Karlsruhe starting in the first quarter of 2001. The feasibility demonstration of the TF coil case is being carried out also by European industry by: Forging trapezoidal tubes with variable wall thickness, casting new modified 316LN type material for the intercoil structure and the parts of the case subject to lower stresses, qualifying the welding and NDT methods to be applied to the heavy thickness (~250mm) to be joined together to form the casing.

1. TFMC Programme

The TFMC is based on the design concept described in the ITER EDA Final Design Report [1]. This foresees the use of thin-walled Nb_3Sn cable-in-conduit conductor [2] which is then insulated and placed in spiral grooves on both sides of a stainless steel radial plate [3].
The TFMC is reduced in size as compared to the ITER TF coils [4]. It will be tested in the TOSKA test facility at FZK Karlsruhe, at first alone and later together with the EURATOM-LCT coil which will generate a background magnetic field. Although the field of 12 T of the full scale coils cannot be achieved in TOSKA, the mechanical, electrical and hydraulical conditions representative of the full scale coils will be simulated.

The main objectives of the ITER TFMC programme are:
- to develop and verify the full scale TF coil manufacturing techniques;
- to establish realistic manufacturing tolerances;
- to bench mark methods for the ITER TF coil quality assurance and acceptance;
- to gain information on the coils operating margins and in-service monitoring techniques.

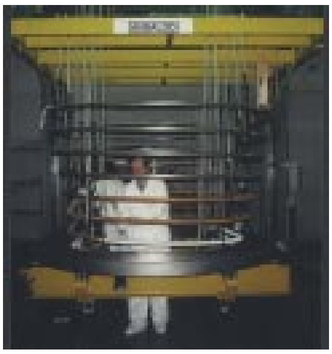


FIG. 1. Conductor Transfer

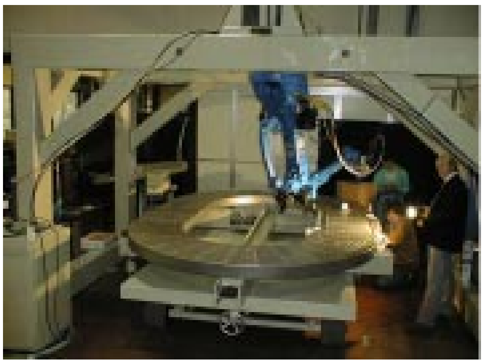


FIG. 2. Cover Laser Welding

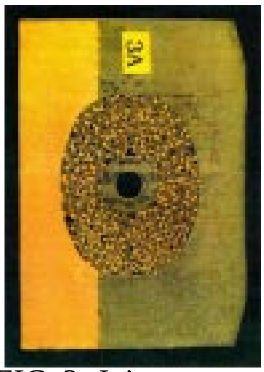


FIG. 3. Joint


FIG. 4. DP Assembly

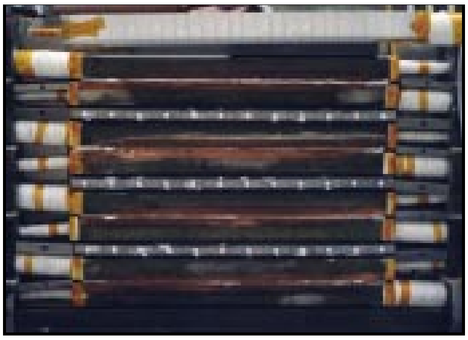


FIG. 5. Joints E-beam Welding

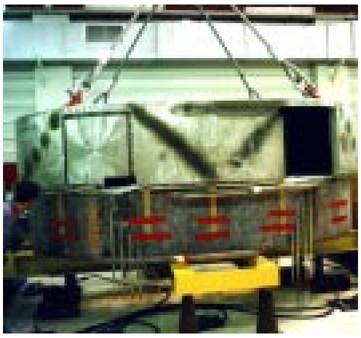


FIG. 6. Case Assembly

The TFMC consists of five racetrack-shaped double pancakes. In each double pancake, the circular conductor, composed of a Nb_3Sn cable inserted in a thin 316 LN steel jacket (similar to the full size ITER conductor), is placed in machined grooves of a radial plate ('react and transfer process') (*FIG. 1*). The insulated conductor is held in a place by covers which are laser welded at the corners of the groove (*FIG. 2*). The single pancake joints are formed by compaction of the cable inside a box, using a shaped cover to reduce the void fraction. The complete cable outer wrap and the substage wrap only from the outer cable surface, are removed to control the AC losses of the joint. The box is formed from steel with a copper sole plate machined from a copper steel composite sheet formed by explosive bonding (*FIG.3*). The single pancake joints are soldered to form a continuous double pancake which is wrapped with glass-Kapton tape and then vacuum impregnated. The five double pancakes are assembled and insulated to ground with a combination of glass fabric and polyimide tapes and then epoxy vacuum impregnated (*FIG.4*). The joints of the double pancakes are at the outer circumference. The joint between double pancake is made by E-beam welding to limit the thermal expansion and distortion of the conductor during welding (*FIG. 5*). The impregnated coils are then placed inside a stainless steel case and the gap between coil and case is filled with insulation (*FIG. 6*). The external dimensions are 3.8 m in height, 2.7 m in width and 0.77 m in thickness. The weight of the finished coil is 31 t.

The test of an integrated system, namely the model coil, is the only way to fully qualify the techniques used during the manufacture which are relevant for the full size coils. Thus, the testing must be representative of the constraints which occur in the full size TF coil arrangement. Furthermore, the tests should evaluate the operation margins of the coil parameters. The testing conditions should also serve as benchmarks for the acceptance tests of the full size coils. In order to minimise the cost of the TFMC the LCT has been used to provide an additional magnetic field. The connection of the TFMC to the LCT is done via an intercoil structure (ICS) which has already been manufactured and delivered to FZK. (*FIG. 7*)


FIG. 7. ICS

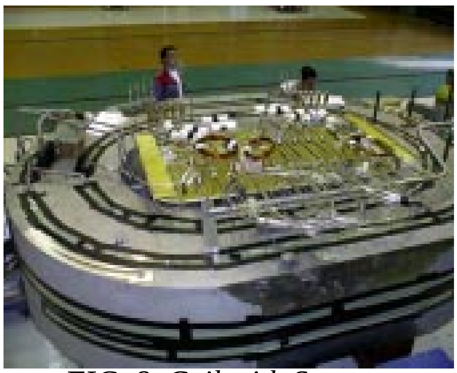
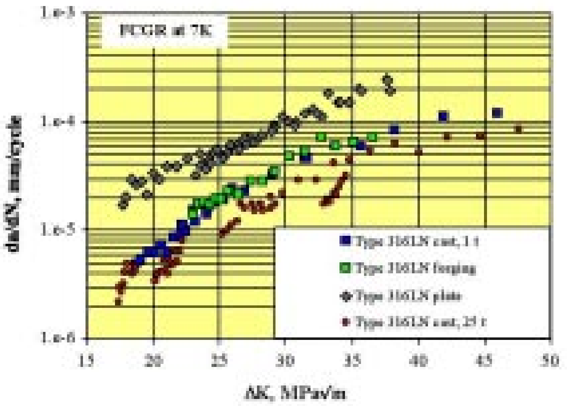


FIG. 8. Coil with Sensors



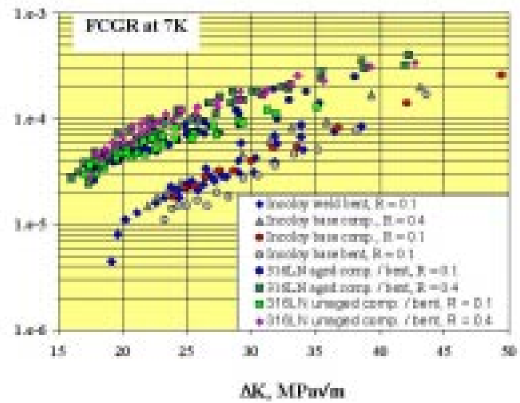


FIG. 9.a) Casing and ICS material b) Jacket material

The conductor for the TFMC has been produced by Europa Metalli and the TFMC is being manufactured by AGAN, a consortium of European companies (consisting of Ansaldo Energia, Alstom, Accel and Noell) and is now nearing completion (*FIG. 8*). The jacket material has been qualified as well as the welds (*FIG. 9*) [6]. The first three objectives indicated above have been reached. The delivery to FZK Karlsruhe is foreseen by November 2000. It is envisaged that the testing of the TFMC will start in the first quarter of 2001.

2. R&D Programme for ITER TF Case and Intercoil Structures

The ITER TF coil cases are designed to support the large in-plane and out-of-plane loads experienced by the TF coils during operation [7]. The case requires, therefore, thick walls (~ 100-250 mm) with good properties for the base material and welds.

The ITER European Home Team has initiated a technological development task [8] to manufacture three partial full-scale models of the case.

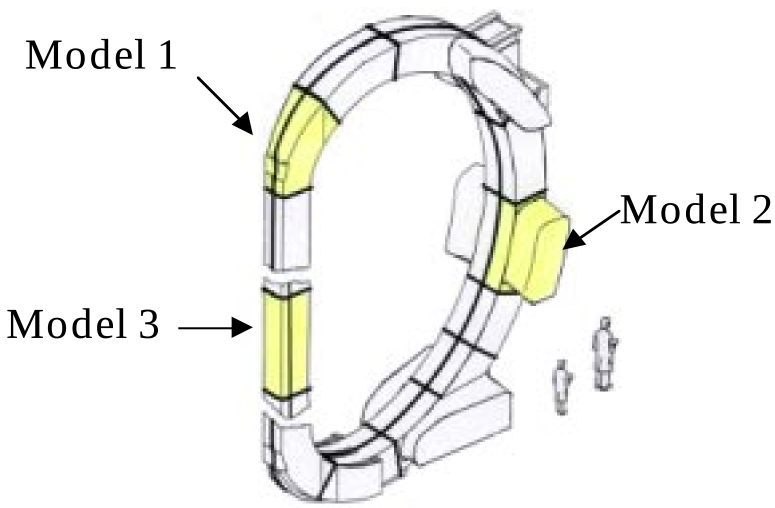


FIG. 10 TF Coil Case R&D

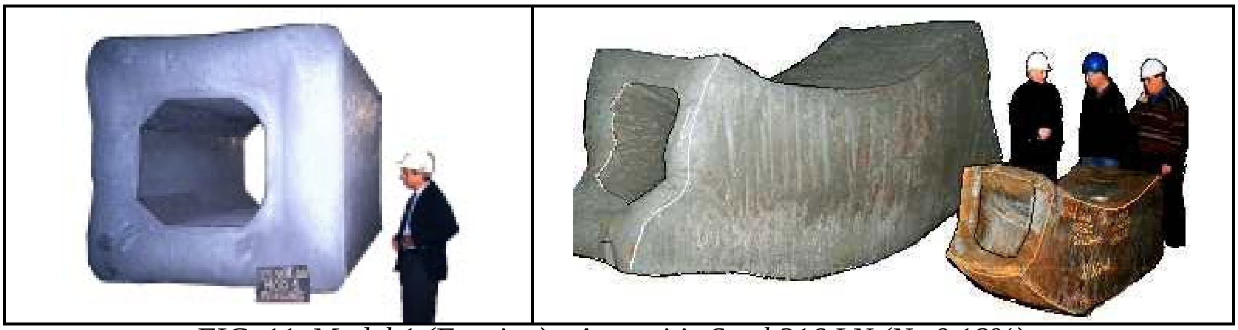


FIG. 11. Model 1 (Forging) - Austenitic Steel 316 LN (N=0.18%)

The scope of the work is to assess the feasibility of such a construction, choose suitable materials and evaluate the achievable material properties, and develop the manufacturing processes and quality control procedures. Model 1 reproduces the geometry of the inboard curved region of the TF coil, where the operational cyclic stresses are highest, Model 2 represents the geometry of one Outer Intercoil Structure, and Model 3 reproduces a portion of the inner straight leg where the highest static stresses are applied (*FIG. 10*). Due to the stringent structural requirements at the inboard leg, it has been chosen to fabricate the case sections located in that region with thick forgings. In the outer regions of the coil, where the stresses are somewhat lower and the geometry of the case and intercoil structures more complicated, cast pieces are a more economical option.

The mechanical properties required at 4 K by the design are very large, such as yield strength > 1000 MPa and ultimate tensile strength > 1500 MPa for forgings, and a yield strength > 750 MPa for castings. In order to achieve these properties, modified versions of the austenitic steel AISI 316 LN have been chosen. For Model 1 it has been proposed to use a stainless steel with higher content of N (0.18-0.2%), similar to the one used in the manufacture of the radial plates for the TFMC. The higher content of N makes welding more difficult, because of the risk of segregations. In order to improve the solubilization of N into the material and improve its weldability, another alloy with a higher content of Mn, has been used for the cast Model 2. In order to test the fabrication methods, Model 1 has been fabricated from a 40 t forged curved tube starting from a 60 t billet, which has been pierced to produce an offset central hole. Several forging operations have then been performed to form the tube into the wedged shape typical of the inner leg cross section and bend it to achieve a curvature similar to the upper region of the TF coil (*FIG. 11*). Typical forging thicknesses have been in the range of 200-350 mm. Model 2 has been produced by casting (*FIG. 12*), starting from an 80 t billet of modified austenitic steel. The thickness of the cast piece, simulating the middle intercoil structure of ITER, ranges from 100 to 250 mm. The same alloy used for Model 2 will be forged for Model 3 to produce two L-shaped sections of the case to test the feasibility of the entire case with the same material.

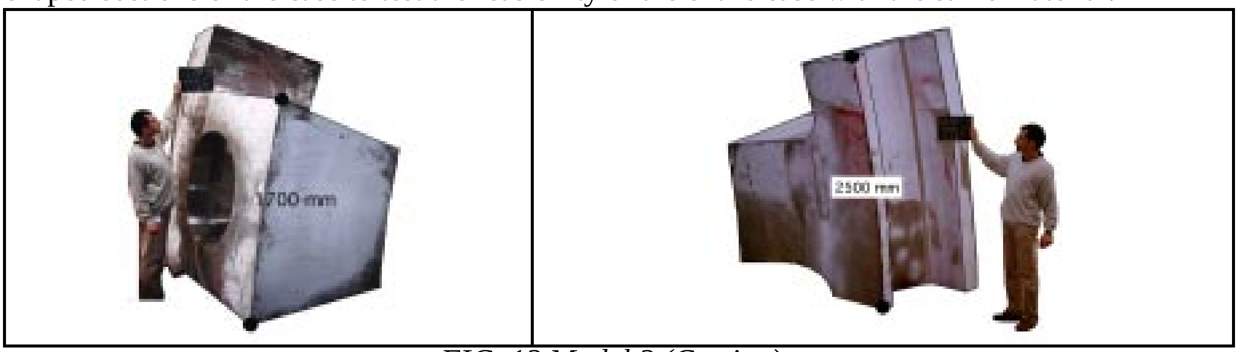


FIG. 12.Model 2 (Casting)

The distortions of the coil case during manufacture, especially due to closure welding with the winding pack located inside, shall be limited and under control. A comprehensive campaign of development and qualification of welding processes has been performed to compare production rates, material quality and geometrical distortions during welding. Several coupons (up to 240 mm thickness) have been produced to optimise the welding parameters, to evaluate the distortions during welding and assess how to reduce them. The work included the measurement of the mechanical properties of the welded joints at room temperature and cryogenic temperatures and the development of specially dedicated Non Destructive Testing procedures to guarantee acceptable quality. It has also been undertaken the development of analytical (finite-element) methods for the prediction of the geometrical deformations and residual stresses due to the welding processes. The models have been benchmarked against the results of experimental measurements obtained on specially dedicated coupons using different welding methods (*FIG. 13*).

Coupon A Coupon B Coupon C1a (R)

FIG. 13. Coupons for Distortion Analysis (Manual TIG Welding - SAW)

3. Final Remarks

The structural materials and manufacturing methods for the construction of the TF coils have been qualified. The validation of the design and analysis methods for the ITER TF coils, as well as the assessment of the operating margins will be done with TFMC tests expected by July 2001. The feasibility of the TF coil case has been demonstrated and the cost optimisation is being carried out.

References

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