CARE NED Work Package 4

Insulation Development: Final Report on Innovative Insulation

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1. Introduction

If Nb_3Sn is actually the best superconductor candidate for the realization of high field magnets, its implementation remains delicate:

- A long heat treatment (about 2 weeks) at about 660°C under a flow of inert gas is required to form the superconducting inter-metallic compound by a solid state diffusion process; that means that no organic material can be introduced in the coil before the treatment.

  At this temperature level, organic material will be degraded, mostly into carbon, critical element in a good electrical insulation. As the treatment is made under inert atmosphere to avoid oxidation of the stabilizing copper, the carbon will not be oxidized, which is a way to eliminate it. So the conventional insulation systems as polyimide cannot be used.

- After treatment, the material is very brittle and strain sensitive. As a consequence, in practice, most of the coils are produced following the “Wind and React” technique.

In the generally used process, the cable is wrapped with a mineral tape and then, wound to form the coil. After the heat treatment, the coil is transferred into an impregnation mould to be vacuum impregnated with epoxy resin. The transfer, as well as the vacuum impregnation is a risky operation.

As an alternative to the glass/epoxy insulation, we have developed a one-step innovating ceramic insulation deposited on the un-reacted conducting cable. The objective is to use the unavoidable heat treatment to form a ceramic and to obtain, at the end of the operation, a coil having a mechanical cohesion, while maintaining a proper conductor positioning and a suitable electrical insulation. The process is described in ref [1, 2].

The feasibility of this innovative insulation scheme has been demonstrated within the framework of an internally-funded Nb_3Sn R&D program at CEA/Saclay [1, 2] and 2 patents have been deposited. The solution of precursors without any organic binder and its application to the fibre-glass tape have been optimized to enable proper pre-impregnation and conductor wrapping. Furthermore, it has been verified that, when subjecting a stack of insulated cables to a temperature cycle representative of the Nb_3Sn heat treatment, the cables bonded together and that the chemical reaction that takes place does not degrade the transport-current properties of the Nb_3Sn wires (Fig.1).

An impregnation facility has been developed which allows preparing several tens of meters at a time. Fig.2 shows the homogeneous deposit layer on a ribbon: the ceramic penetrates entirely the fibres.

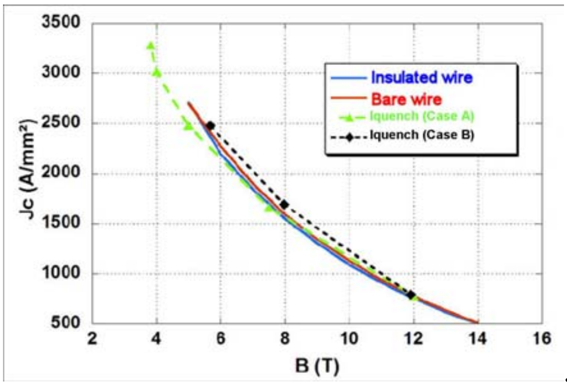

Fig.1: Comparison of the critical current values obtained on VAMAS sample type and the quench current values obtained on the demonstrator [3].

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Fig.2: Innovative insulation tape with ceramic precursor.

2. NED objective

Due to a lack of human resources, the work on the innovative insulation was put hold at CEA and the NED Steering committee was informed of the situation. The work was restarted in April 2006, thanks to the arrival of a NED-funded additional staff.

At this time, in accord with the NED Steering Committee, the test program was redefined in order to focus on the characterization and the improvement of the mechanical properties of insulated cable stacks representative of magnet coils and the task about testing the influence of tape weaving pattern was dropped out.

3. Experimental Results

3.1- Ceramic solution

Because of the natural origin of a component in the precursor solution, some changes in the behaviour can be observed after a new delivery or a long period of storage of this component. Some additional studies have been performed to complete the control of the solution.

Two issues have been investigated:

- The foaming of the ceramic samples during the heat treatment, which has been eliminated by a modification of the preparation method of the ceramic powder required for the qualification tests of the ceramic matrix.
- The degradation of the rheological behaviour of ceramic suspensions, attributed to variations in the clay properties, likely due to a granulometric classification in the clay bag; clay was restocked and a study of the sampling procedure to avoid rheological behaviour drift was carried out.

3.2- Mechanical tests

The most critical issue in the innovative insulation development is the mechanical characterisation of this insulation.
In a first time, we have been interested in the behaviour of the insulation under compression stress. The used method was derived from the classical technique used to qualify the quadrupole conductor and insulation: perform the compression test on stacks of conductors prepared with electrical insulation.

The tests are carried out with an Instron screw-driven machine, which allows tests at room temperature as well as in cryogenic conditions, the load being measured with a 150 kN cell (Fig.3). The direction of the applied stress is perpendicular to the cables (Fig.4). The samples are submitted to 3 cycles of uniaxial compression from 0 kN to the chosen force, which is 150 kN at maximum.

Preliminary and interesting results were obtained using this method with 10 cm long stacks [ref.1].

For this study, the test program had to be adapted to take into account the NED insulation specification parameters as defined in the document ref [4].
Indeed, the NED specifications indicate a maximum pressure of 200 MPa in normal use, so we had to introduce some modification to allow the samples to be tested at this rate of compression with our press. As the measurement cell allows a maximum charge of 150 kN, the length of the stacks has been adapted and defined at 50 mm (about half the length of the twist pitch of the cable).

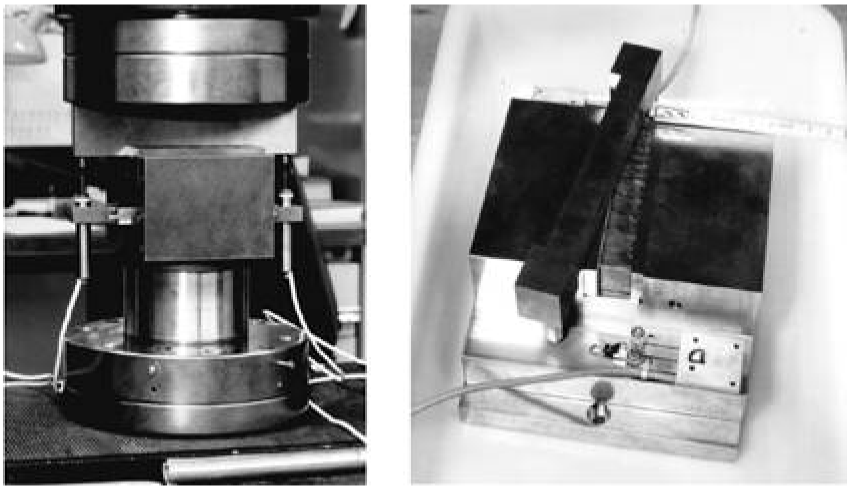

Fig.3: Measurement cell for compression test on stacks.

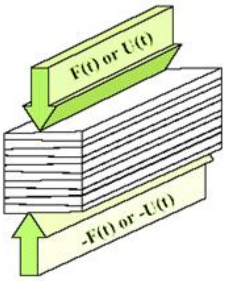

Fig.4: Direction of the stress forces on the stack during the compression test.

Remark: for the moment, the baseline thickness per cable for the ceramic insulation is about 0.4 mm and not 0.2 mm as required, because of the initial thickness of the available S glass tapes (0.1 mm) and the need to have enough material deposit on the tape to allow the reaction during the heat treatment.

The tests have been performed on stacks of eight Rutherford type Nb_3Sn cables wrapped with innovative insulation and reacted, without additional solution around the cables. Moulds have been designed and manufactured to produce insulated stacks of 50 mm long, relying on different pre-compressions during the heat treatment (Fig.5), as it is required in the mechanical properties of the NED insulation specification (20 MPa in design, 40MPa in failure).

Fig.5: Heat treatment mould.

2 samples can be prepared in the same mould, with same parameters.
The moulds were closed under the press and a pre-compression of 13 MPa to 55 MPa was applied to the samples. The idea is to study this effect on the mechanical properties of the insulation.

In a first step, the samples were submitted to 3 cycles of uniaxial compression from 0 MPa up to a stress level of 75 MPa at room temperature. One of the results is presented in Fig.6.

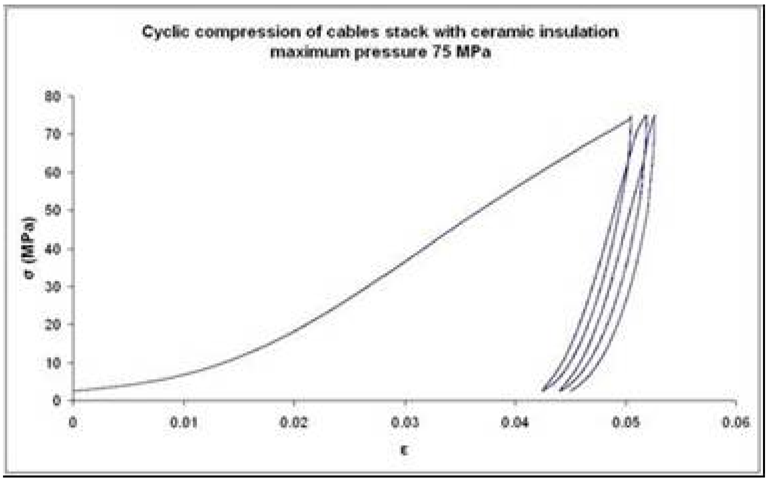

Fig.6: Cyclic compression on 8 cables stacks.

As some fracture lines have been observed on the sides on the samples (Fig.7), the tests have been stopped. In fact, some of these fractures have been already observed when the samples are extracted from the reaction mould before the mechanical test itself.

Fig.7: Stack of insulated cables reacted with a pre-compression, after outing of the reaction mould and relaxation of the cable stack

When one mould is closed under the press, some compression appears on the 2 stacks of eight conductors (for instance, about 8 mm in total under a load of 10 MPa) and is maintained during the sintering process and the ceramic formation (Fig.8.a).

In the procedure we have used, it was necessary to extract the samples from the reaction mould to put them in the compression test setup. During this step, a relaxation of the sample appears and a high level of stress in flexion is reached on the side of the cable, on the thin film of ceramic (Fig.8.b), which can produce some fractures on the sides on the samples (Fig.7). At this time, the compression stress imposed during the heat treatment has been released and what is observed is the relaxation and the rearrangement of the cables.

During the compression test, no degradation is observed between the cables, where the insulation is submitted to pure compression stress.

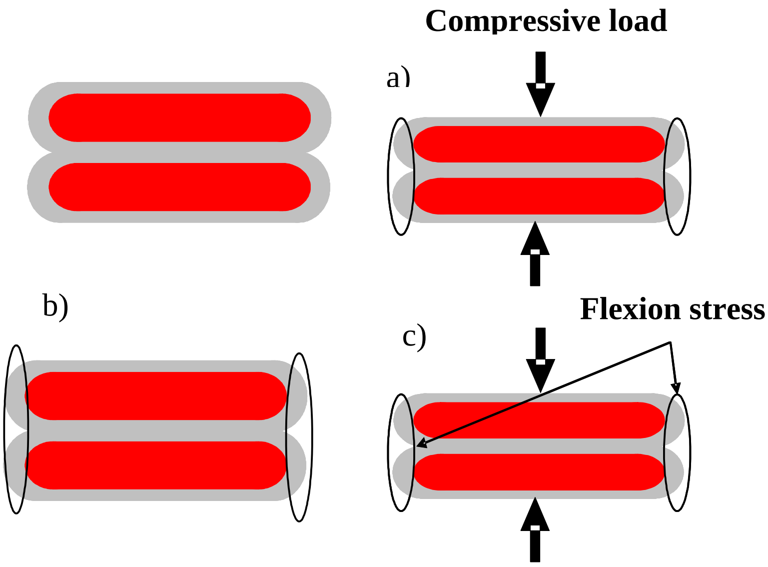

Fig.8: Flexion stress during the sample life. a) the mould is closed - b) the samples are extracted from the mould – c) compression test

If the compression tests are performed on stacks of cables without insulation, a similar behaviour can be observed, showing that the relaxation comes from the cable itself (as it can be seen on Fig.9).

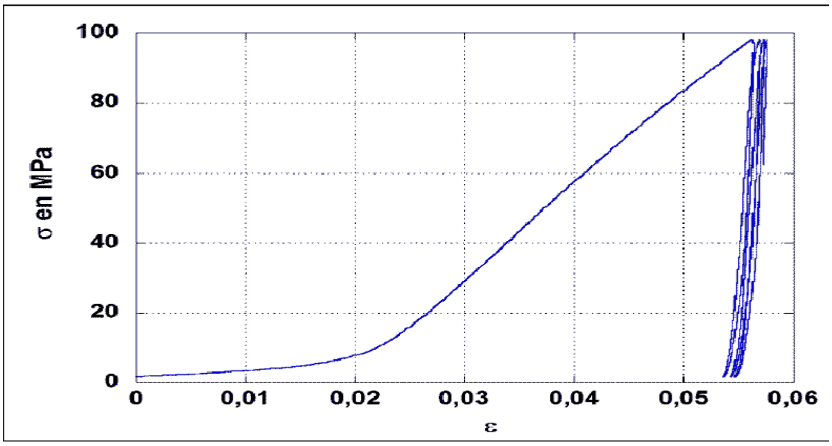

Fig.9: Compressive deformation of a 10 cables stack without insulation.

The behaviour of the stacks samples seems to be disturbed by the behaviour of the cable on this short length (50 mm, about half the length of the twist pitch).

3.3- Parallel studies on a small coil

In parallel with the NED studies, the developments of small solenoids able to be tested in our experimental setup have continued. A solenoid was modelled, designed and tested in a high external magnetic field in the CHRISTIANE test facility [5]. During the tests, the quench limits have been imposed by the strand and the insulation was not damaged also with a stress level of about 35 MPa in compression and 65 MPa in tension. These stress levels reached, are related to the peak field inside the coil and can not be increased in the actual configuration.

After these very encouraging results, a new coil with a higher performance has to be built to approach the limits of the technology. It is a part of the motivation to work in the NED SMC (Short Model Coil) program.

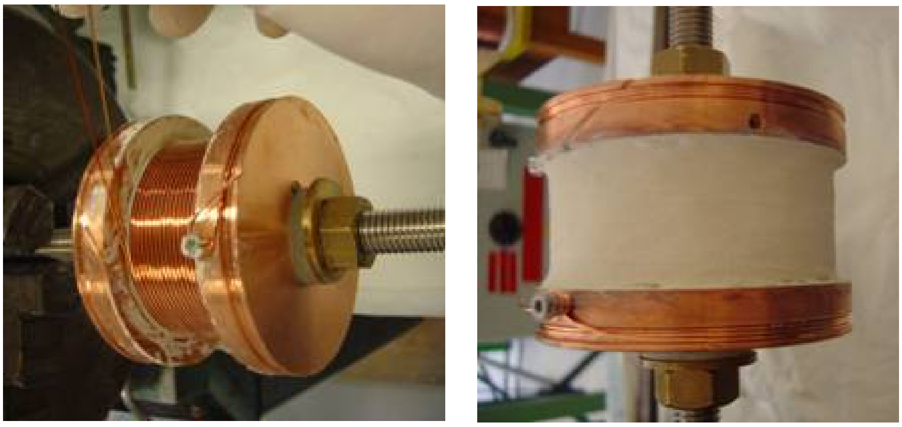

Fig.10: View of the coil during winding

4. Conclusion

The retained method, compression tests on stacks of insulated conductors, seems not to be adapted to qualify the mechanical performances of the innovative insulation (probably due to the geometry of the samples). So we will have to reflect upon the right way to extract the required parameters and probably define a new sample design.

To complete the qualification program of the insulation, some tests have to be performed:

- Thermal characterisations are planned to be performed in framework of the EU contract *FP7-IA Eucard-WP6-task2: Support studies.*
- The electrical tests will be completed with dielectric measurements on the insulation.
- The radiation hardness, expected good, will be verified.

In parallel of this study, we are working in the NED SMC (Short Model Coil) program on the design and the manufacture of racetrack coils (Fig.10). The idea is to build a short model coil with innovative insulation having the same structure and the same external dimension as RAL SMC coils. In a first step, a prototype will be built using the dummy conductor produced at CERN to qualify the manufacture procedure and then, 2 coils with ceramic insulation will be produced and tested in the SMC test setup.

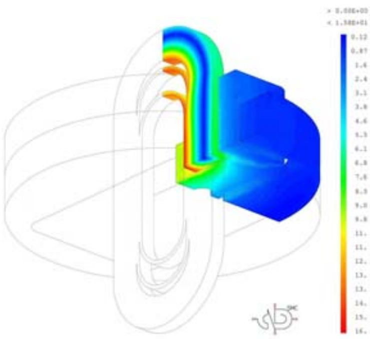

Fig.10:CAST3M model of a SMC coil (Courtesy of P.Manil).

5. Acknowledgements

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6. References

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