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***Abstract*—** The NSTX TF coil assembly experienced a failure in the TF center bundle during pulse number 143912 on July 20, 2011. A short circuit between turns 14 and 30 spread to turn 13 and resulted in melting of approximately 2 kg of copper and ejection of copper and solder from the cooling channels at the lower end of the TF bundle. An autopsy of the coil was immediately begun by PPPL personnel that included cutting numerous sections from the affected region of the coil and examining the chemical makeup of the insulation. In addition, careful machining to isolate various areas of turn to turn insulation uncovered suspicious spots that exhibited low resistance. This paper will present the methods used to isolate the location and identify the causes of the failure in the coil bundle and the design changes made to the NSTX Upgrade TF bundle and fabrication processes to prevent a recurrence of the fault.

***Keywords*—** NSTX-U, TF Coil, epoxy, resin, NSTXU, FSW

I. Introduction

The National Spherical Tokamak eXperiment (NSTX) is the flagship fusion experiment located at the Princeton Plasma Physics laboratory. In July 2011, NSTX was beginning to resume operations after a shutdown for diagnostic and facilities upgrades. It was the last run period planned for the existing machine before it was scheduled to be overhauled with a new TF bundle and structural improvements to advance its performance [1][3]. Only one normal pulse was run the previous day without any indications of a problem. During the first pulse the following day the TF Bundle developed a short between turns 14 and 30. The current during the shot was ~54 kA. (Max. rating is 71.2 kA.).

After electrical tests were performed on the on the failed bundle it was determined that it could not be repaired insitu. The decision was made to remove the bundle and begin the NSTX Upgrade outage approximately 6 months early.

II. Description of the Failed TF Coil Bundle Construction

A. TF Coil Design Parameters

- Thirty Six (36) conductor NSTX TF bundle assembly is the inboard leg of the 36 turn toroidal field coil system.
- Water cooled CDA 107 (OFHC + silver) copper.
- Hardness shall be Rockwell F 70 min. (Vickers HV 76) and compatible with the min. yield strength
- Insulation: B-Stage epoxy/glass (CTD-112P).
- Two (2) layer, 36 turn assembly.
- The TF is designed for operation at 35.6 kA with a 5.3 s ESW or 71.2 kA with a 1.3 s ESW. (The peak temperature for both cases is 95 C)
- Resin Type: TGDM epoxy, aromatic amine cure agent, Composite Technology Development (CID), Boulder, Co
- Glass tape: S-2 (satin weave) std. silane finish Temperature Class: 180° C
- Nominal Thk.: 0.0075 in. (0.19 mm.) tape
- Nominal Width: 1.0 in. tape
- Solder Used in Copper Tube Joint
- Solder: 95% Tin/ 5% Antimony soft-solder
- Flux: zinc chloride based liquid flux

B. History of the Failed Bundle

The failed Inner TF bundle began fabrication at PPPL in 2003 and was commissioned for operation in early 2004.

The bundle was operated for a seven year period with over 20,000 pulses. The bundle consists of two layers of 36 copper turns, each conductor is cooled by a copper tubing cooling passage soldered into a groove in the edge of the conductor. During assembly, each conductor was sandblasted primed and insulated with B-stage insulation that is thermally cured in a press mold to bond the conductors into a single column for mechanical strength. The bundle was fabricated in quadrants to help maintain dimensional control and make the final assembly easier. The quadrants are then placed into a full mold with 0.040" additional b-stage glass/epoxy and cured a second time to bond the quadrants into a single bundle.

After final machining, each conductor is prepared for assembly by the groove and tubing with abrasive pads to remove surface oxides. They were then wiped down with and industrial degreaser to remove any remaining surface oil or grease. The tubes were positioned into the groove, fluxed with zinc chloride based flux, and soldered using an oxy-acetylene torch and 95-5% Tin-Antimony soft solder at 495-510°F.

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Conductors are then filed smooth of excess solder, sandblasted, primed and wrapped in B-stage epoxy impregnated tape before being assembled into a 9 conductor quadrant press-mold to be cured.

After the epoxy has been cured and removed from the mold each quadrant undergoes a 200 psi test of the cooling passage and an electrical hipot test at 3kv. During construction, tests on the quadrants revealed one with 3 pairs of adjacent conductors having lower, but still acceptable, resistance (100-300 Meg-ohms) than the other quadrants (3-50KMeg-ohms). It was decided to place the lower resistance pairs away from the coil lead positions which were operated at higher voltage potentials. The turn to turn insulation thickness was 0.065" which saw a maximum, but modest, voltage stress of 970 volt/65 mils. The failed turns were in the quadrant that tested lower during the coil construction.

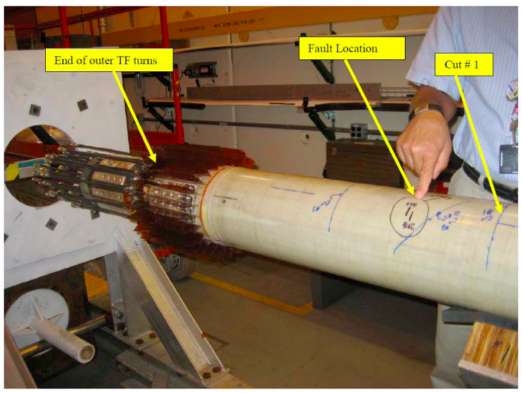

Fig. 1. Coil being marked for cutting

C. Location of the Failure

The location of the short along the length of the TF Bundle was determined using resistances between the shorted conductors. The coil was marked at the calculated fault location, 31", from one end and a ~12" section was removed centered on the fault to perform the forensic dissection. The removed section was further cut into 2" thick sections to reveal the location where the

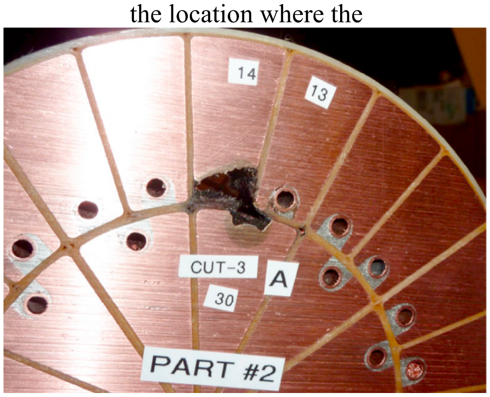

Fig. 2. Coil slice showing the origin of short

short was believed to have originated. Figure 2 shows cut 3 on part 2 which was made at the location of the fault. The remainng two conductor pairs that originally tested low were found in a removed section which was further dissected longitudinally to reveal the interface between the insulation and copper at the low resistance point (Fig 3). The insulation facing the solder was seen to have brown colored spots and lines. The discolorations were similar in color to the solder flux used to install the cooling tubes. These spots were isolated using an ohmmeter with 10 Mohm range to test for the lower resistance locations. Many of the discolored lines were along the edges of the solder as if something had wicked out of the copper/solder interface.

III. Forensic Tests

Forensic tests were planned to learn the cause of the failure and to use the information for the design and fabrication of the upgraded TF bundle. The coil section was sent to an outside laboratory to have tests performed and evaluated on the section. Rockwell hardness tests were performed on the conductors in the region of the failure to determine if there was any evidence of work hardening that might contribute to a fatigue failure of the metal. Surface Electron Microscope and Auger analyses were performed on the the colored stains in the insulation to identify their composition. Photomicrographs were performed on the cooling tube joints to identify any defects which may exist.

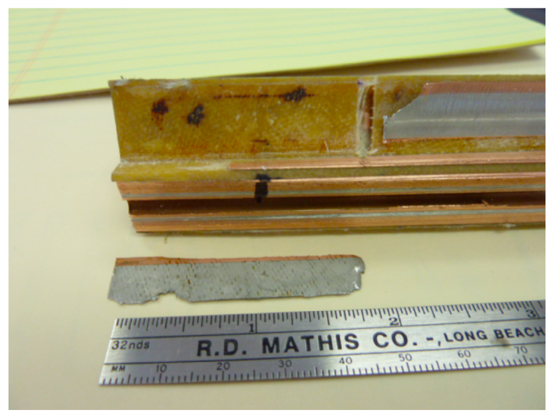

Fig. 3. Dark colored stains appeared to be zinc chloride

A. Test Results

The forensic examination revealed no evidence of cracks or other defects in the cooling tubes (longitudinal or horizontal) or in the copper conductors. Photomicrographs of the cooling tube solder joints did reveal lack of bond and some gas entrapment in some areas.

The Rockwell B measurements can be seen on the sample in Figure 5. They were very similar to those measured on an unused section of copper from the same lot and an undamaged section from the coil indicating fatigue did not contribute to the failure.

The Photomicrographs taken of the copper tube solder pockets revealed sections with lack of bonding and gas entrapment defects. In addition macroscopic inspection of the failed section revealed a remelt condition which alloyed the copper tube, the surrounding solder, and adjacent copper bar to form a brass colored alloy. Spectrographic analysis of the alloy confirmed the remelt was an alloy of principally copper, plus tin and antimony. The Photomicrographs also indicated no physical damage was present to the turn to turn insulation.

The Scanning Electron Microscope (SEM) and Auger analysis of the colored stain at the insulation / copper interface were performed to determine the elemental composition. These tests were compared to clean insulation samples to isolate the composition of the colored stains. These tests revealed that there were high levels of Zn and Cl in the colored stains which are the main constituents of the flux used to solder the cooling tube.

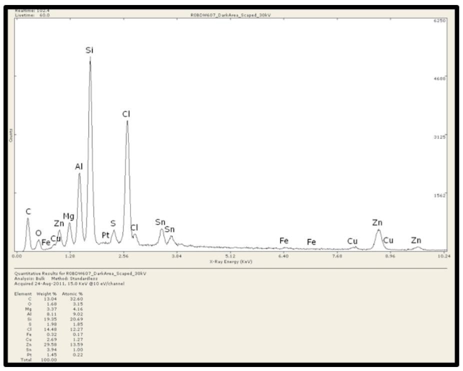

Fig. 4. EDS Tests found high levels of Zinc and Chlorine

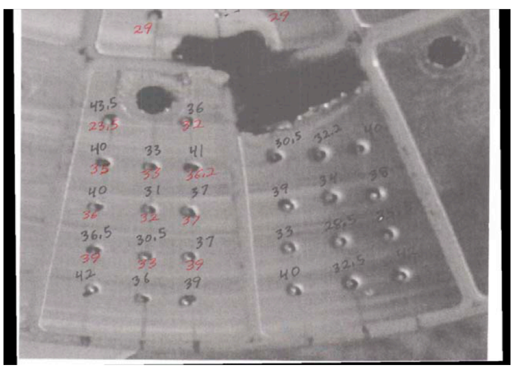

Fig. 5. Rockwell tests were perforned on conductors to rule out fatigue

B. *Cause of the Failure*

There were no visual signs of overheating in any of the samples cut from the bundle and a review of the operational data taken during the shots revealed the coil was being properly cooled during and after the shots thus eliminating lack of cooling as a potential cause.

Furthermore calculations indicated the stresses seen by the insulation were well within the allowable values for the materials used for construction.

While the actual cause of the failure may never be proven definitively the evidence uncovered during the forensic test has led to the following failure scenario as the most likely:

- Residual solder flux displaced and/or contaminated insulation in localized regions during the elevated-temperature curing (baking) of bundle quadrants during the construction process

- While all of the conductors met the acceptance criteria, the acceptance testing (3 kV Megger) of the bundle quadrants "tracked" in 3 discrete locations. Subsequent testing was performed at decreased voltage levels and the normal operating voltages were even lower.

- The seven (7) years and 20,000 pulses of operation on NSTX further degraded these localized insulation defects. The degradation is believed to have been caused by repeated electrical conduction and/or continued chemical degradation due to the presence of zinc-chloride in the insulation.

- Finally, one of the insulation defects degraded enough to cause an arc between conductors.

- In addition to the evidence found during the forensic testing a literauture search was performed and uncovered a technical paper that had documented similar failures caused by Zinc Chloride fluxes [4].

IV. Impact and Design Changes on NSTXU TF Bundle

As part of the NSTX Upgrade the Inner TF Bundle was redesigned to meet the GRD requirements of higher currents and pulse length. As a result of the failure described above the new bundle design was examined to determine if improvements could be made to the design or fabrication processes to mitigate the cause of the failure. The upgraded Inner TF bundle has 36 turned that are no longer arranged in two layers but are arranged in a single layer (Table 1). The conductors are now cooled with a ACR copper tube soldered into the side of the conductor. This new configuration reduces the turn to turn voltage stresses from 970 volts to 28 volts.

To eliminate the Zinc Chloride from the process an Organic Flux was used to solder the tubes into the conductors. The solder and flux was prepared in advance as a paste that was preplaced below and around the tube in the groove. In place of a torch brazing process the conductor was heated on a resistively heated "hot plate" to the solder temperature and a torch was only used to touch up the solder [2]. The conductor was held at temperature long enough to ensure the flux was consumed in the process. In addition a more thorough cleaning process was used after the soldering to remove any remaining flux and then baked at 170C to ensure that the last remaining traces were bake out [3].

TABLE I. DESIGN PARAMETERS OF THE PRESENT DESIGN AND UPGRADE

Description	Present Design	Upgrade Design
Operating Current	**1013 volts**	**1013 volts**
Number of Turns	**36**	**36**
Number of Layers	**Double**	**Single**
Cooling	**water**	**water**
Maximum T/T Voltage stress	**970 volts**	**28 volts**
Maximum T/T voltage/mil	**14.9 volts/ mil**	**0.432 volts /mil**
Maximum volt/mil across leads	**14.9 volts/mil**	**9.65 volts/mil**
Turn to Turn Insulation thickness	**0.0648 inch**	**0.0648 inch**
Groundwrap insulation thickness	**0.054 inch**	**0.222 inch**
Insulation Scheme	**B-stage (Pre-preg)**	**VPI**
TF Conductor material	**C10700**	**C10700**

V. CONCLUSION

By performing a thorough visual and chemical forensic analysis of the failed TF Bundle the most likely failure scenario was found. Using this information significant and potentially critical changes were made to the upgrade TF Bundle to prevent a failure from similar causes in the future.

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