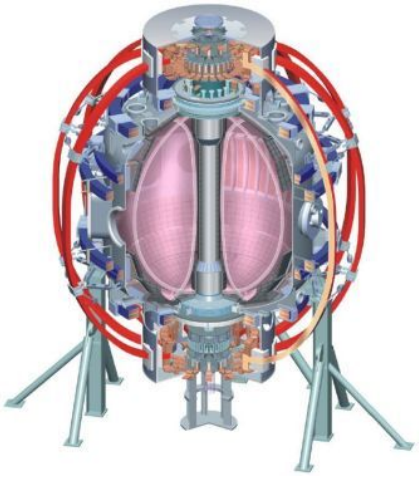

NSTX TF Bundle Failure

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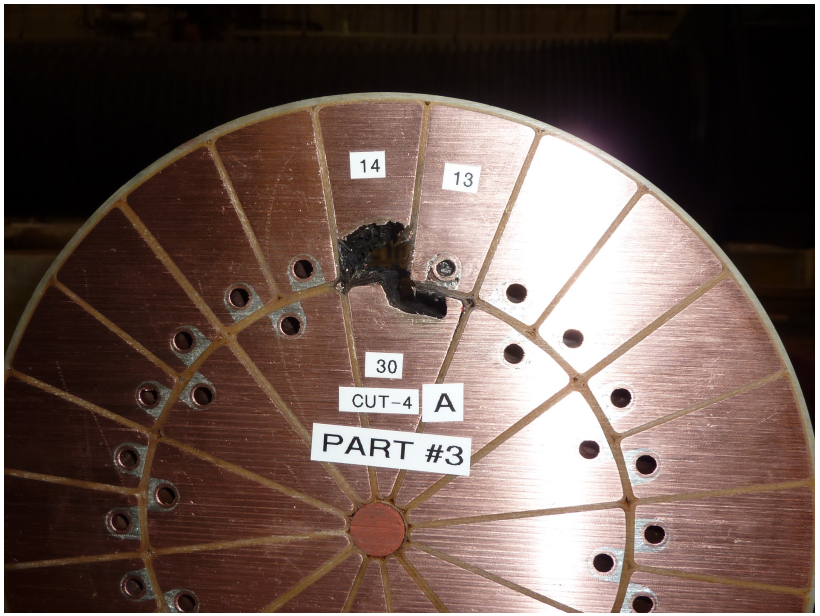
September 13, 2011

U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL PRINCETON PLASMA PHYSICS LABORATORY

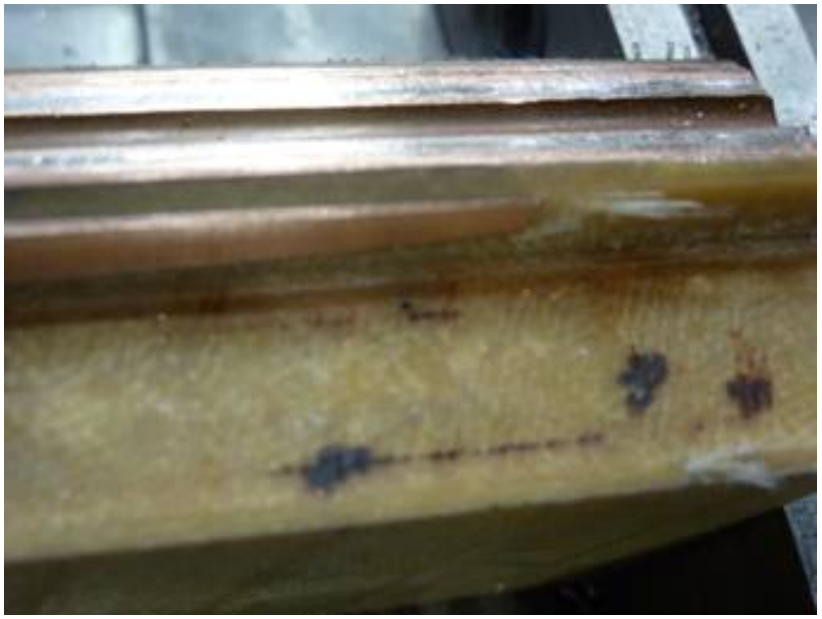
The NSTX Toroidal Field (TF) Bundle failed on July 20, 2011:

- Non-repairable internal arc damage
  - It would take about a year to build a replacement, install and resume plasma operation (replacement copper on-hand)
- PPPL and NSTX Team subsequently concluded that the best path forward is to begin the Upgrade outage immediately (previously scheduled for April 2012)
  - A successful Upgrade FDR was completed in June 2011
  - We are ready to begin the Upgrade outage
  - But, in light of the failure, we need to evaluate any risks in the Upgrade bundle design before moving forward



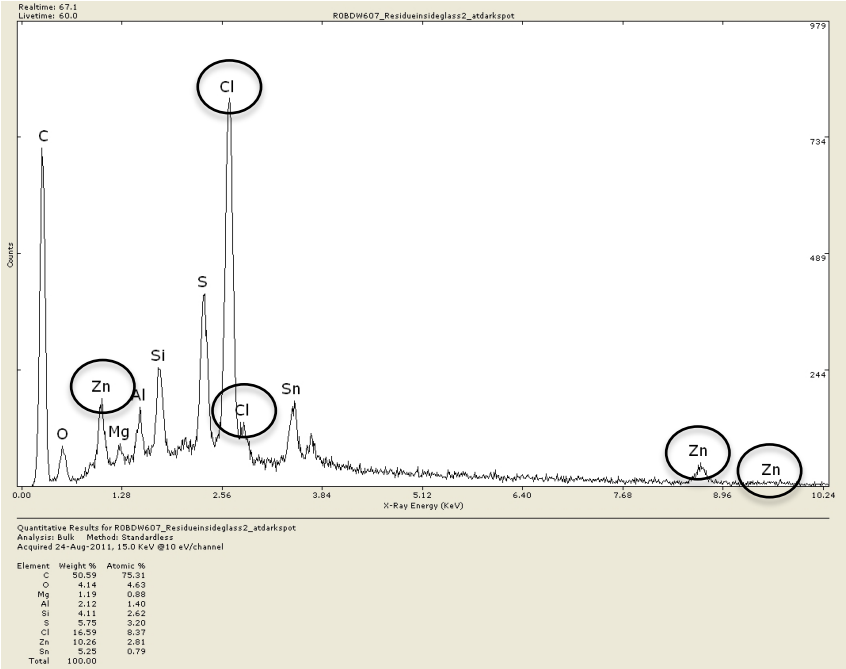
An autopsy of the failed bundle was performed:

- Failure of conductors was noted to be 1 of 3 pairs that were sub-optimal during acceptance tests
  - 100-3000 M-ohm versus 30,000-50,000 M-ohm during 3 kV quadrant tests
- Forensics yielded convincing evidence with regard to both remaining sub-optimal pairs
  - Found 1-10 M-ohm conductive path in a distinct location measured with an ohmmeter
  - Discoloration of epoxy/glass insulation system
  - Localized resin-poor area



Independent analyses of the copper and insulation were obtained:

- Metallurgical analysis of copper and tubing found nothing unusual or indicative of excessive stress or fatigue
- Analysis of the insulation verified the elevated presence of zinc and chlorine, two components of the flux used to solder the cooling tube in the copper conductor
- Literature search showed problems with zinc-chloride in insulation systems

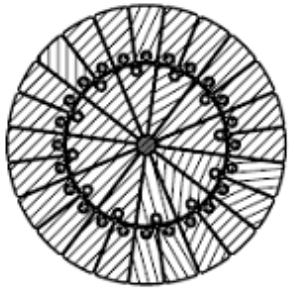


A likely failure scenario was developed:

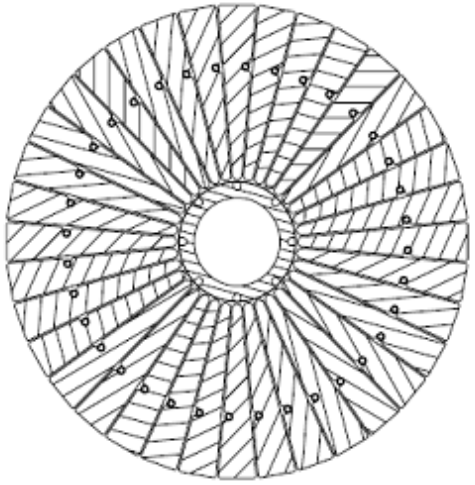
- Residual solder flux displaced and contaminated insulation in localized regions during the elevated-temperature curing (baking) of bundle quadrants
- Acceptance testing (3 kV Megger) of bundle quadrants "tracked" in 3 discrete locations
  - All conductors met acceptance criteria
  - Subsequent testing was performed at decreased voltage levels
  - Normal operations were at still further decreased voltage stress
- Subsequent operation on NSTX further degraded these localized insulation defects
  - Seven years and more than 20,000 pulses
  - Repeated electrical conduction and/or continued chemical degradation due to zinc-chloride
- Finally, one of the insulation defects degraded enough to cause an arc between conductors
  - This was in the highest voltage stress region

The Upgrade design addresses the determined failure mechanism:

- Single-layer versus double layer design
  - Reduced voltage stress between conductors (30 volts)
  - Terminal voltage (1 kV) across quadrant segments where there is increased insulation
- VPI versus B-Stage glass resin system
  - More homogenous insulation system without voids
- Bundle manufacturing process will be greatly improved to address residual solder flux
- A spare TF/OH Bundle will be fabricated
- Increased maintenance



Old



New

An independent review panel was assembled:

Bob Benson*, ORNL (retired)
Kevin Freudenberg**, ORNL
George Ganetis*, BNL
Nicolai Martovetsky***, LLNL (US ITER)
Joe Minervini***, MIT
Brad Nelson (chair)*, ORNL (US ITER)
Dick Reed**, NIST (retired)
George Velev***, FNL
Gary Voss**, UKAEA
Peter Wanderer***, BNL

* Attended in person
** Attended via telecon/GoToMeeting
*** Unable to attend

The review was successfully held on September 7, 2011:

From the close-out report:

PPPL team did an outstanding job of investigating the TF bundle failure.

Flux contamination appears to be most likely cause of fault. The problem appears to have existed from the time of fabrication of the TF bundle quadrants.

It appears that the turn-machining contract can go forward with low risk.