PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3777
UC-70

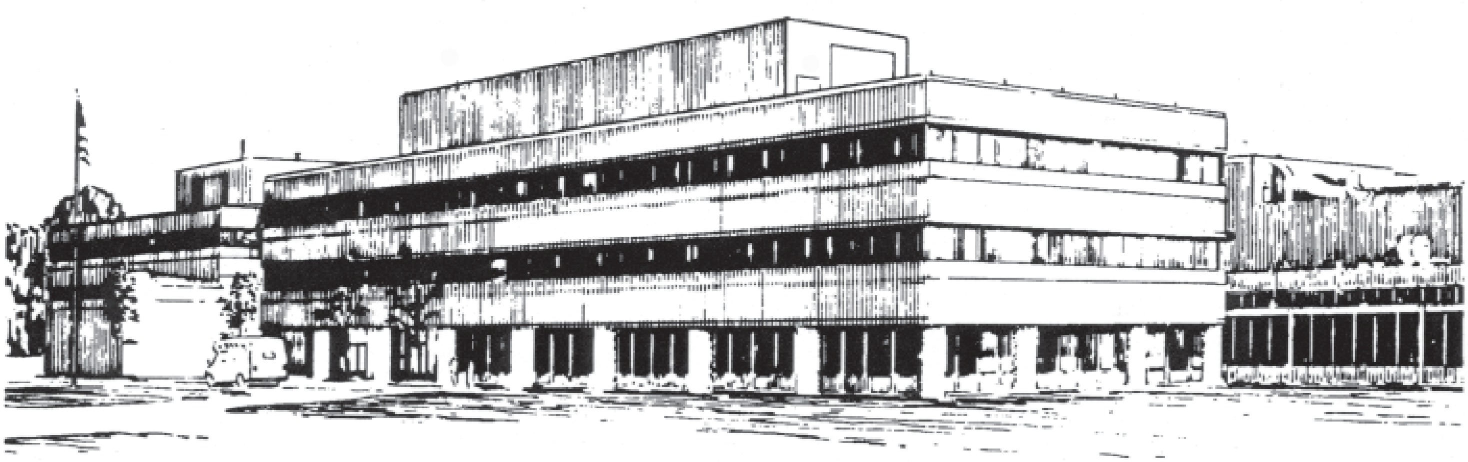
PPPL-3777

TFTR D&D Project: Final Examination and Testing of the TFTR TF-Coils

by

Irving J. Zatz

January 2003



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TFTR D&D PROJECT

FINAL EXAMINATION AND TESTING OF THE TFTR TF-COILS

December 18, 2002
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Appendixes are available from I. Zatz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543 (izatz@pppl.gov).

1. INTRODUCTION

In operation for nearly 15 years, TFTR was not only a fusion science milestone, but a milestone of achievement in engineering as well. The TFTR D&D program provided a rare opportunity to examine machine components that had been exposed to a unique performance environment of greater than 100,000 mechanical and thermal load cycles. In particular, the possible examination of the TFTR Toroidal Field (TF) coils, which met then exceeded the 5.2 Tesla magnetic field machine specification, could supply the answers to many questions that have been asked and debated since the coils were originally designed and built. A test program conducted in parallel with the D&D effort was the chance to look inside and examine, in detail, the TFTR TF coils for the first time since they were delivered encased to PPPL. The results from such a program would provide data and insight that would not only benefit PPPL and the fusion community, but the broader scientific community as well.

A test program was proposed that would set aside a number of selected sections from the twenty TFTR TF coils as they were removed during D&D. These sections would be cut from the coils in several different areas including the nose, back leg, water fitting and lead block regions, concentrating on those known areas whose performance was questioned during TFTR operations.

The approved test program included documented visual inspections and photography during all phases of disassembly and testing. Physical examinations of the coils were performed to determine consistency of coil manufacturing techniques, including status of the potting compound, quality of turn-to-turn epoxy impregnation and bonding, and determination of the cause of coolant leaks during operation. Selected chemical and metallurgical analyses were conducted to determine if the composition of the materials have altered and to identify unknown materials. Multiple mechanical test samples in various orientations were cut from several magnet and case locations to check for consistency and range of material properties.

With the exception of the chemical and metallurgical analyses, this test program was performed entirely at PPPL.

2. TF COIL DESIGN AND MANUFACTURING OVERVIEW

Each of the twenty TFTR TF coil assemblies was comprised of a copper alloy magnet enclosed in a four segment bolted Nitronic 33 stainless steel case. The case was necessary to provide stiffness and strength to withstand the loads produced by 73.3 kA of current in the magnet, which generated a maximum toroidal field of 5.2 Tesla. This field resulted in a net centering force of 6.1 million pounds and an overturning moment of 105 million inch-pounds in each magnet. Due to the exceptional overall performance of the TF coils, these design levels were exceeded late in the TFTR program. Specifically, the 44-turn, spiral wound, two-pancake magnet was made of a variation of CDA 104 silver-bearing OFHC copper alloy, extruded and drawn to a minimum yield strength of 32 ksi [Reference 1]. Turn thickness varied in three groups from 0.552-inch to 0.677-inch to balance temperature gradients in the coil. The coil insulation system was comprised of the following [Reference 2]:

- Turn-to-turn insulation made up of multiple half-lapped layers of 0.007-inch thick glass fiber tape
- Barrier strips and glass filler insulation between pancakes
- Ground wrap insulation
- Potting compound inserted after the coil was installed in the case - inner case surfaces were treated with a parting agent (mold release) to prevent bonding of the potting compound to the case

The case bolt material was Inconel 718. As a historical footnote, the TFTR coil case was originally designed to be made from titanium alloy with these Inconel bolts. For a variety of reasons, late in the design stages of TFTR, the case material was switched to Nitronic 33 stainless steel, which has higher elastic modulus but lower strength than titanium. This design change was made because it produced a more favorable distribution of load within the coil. The high strength Inconel bolts bearing on the lower strength Nitronic case material may have resulted in local yielding of the case and could have been a contributing cause to the bolt loosening incident which temporarily hampered TFTR operations in the early 1990's.

3. THE EXAMINATION AND TEST PROGRAM

3a. IN THE TFTR TEST CELL

A baseline examination and test program was outlined [Reference 3] with the expectation that variations could occur as conditions warranted. When dealing with structures as large and complex as TFTR components, coupled with the requirements and schedule of the D&D program, flexibility becomes critical. As initially planned, sections of TF Coils #3 and #18 would be set aside to be used to prepare samples for a variety of mechanical, metallurgical and visual tests. These two coils were specifically targeted because they had been the sources of some of the most nagging coolant leaks during TFTR operations. Over the years, TF #3 had developed leaks at several of the fourteen water fittings at the base of the coil. Numerous well-documented attempts [examples References 4 & 5] were made to resolve these leaks, but none had been completely successful, ultimately leading to the substitution of Fluorinert (with a high electrical resistivity) for the de-ionized water as the TF coil coolant.

It has long been suspected that the water fitting material that was brazed to the OFHC copper TF conductors may not have been oxygen free copper, resulting in potential hydrogen embrittlement which could lead to cracking and leaking in the water fitting regions.

A chronic leak developed in the lead block region of TF #18 that was speculated to have originated in the lead spur joint within the body of the coil. This leak could not be rectified despite numerous in situ inspections and attempted remedies [example Reference 6].

Although TF coils #3 and #18 were targeted for mechanical and metallurgical testing, each of the other eighteen TF coils were visually inspected for any anomalies that could provide useful data. The usual D&D procedure was to remove each of the ten two-coil and vacuum vessel segments from the TFTR pedestal (Figure 1) following diamond wire cutting (Figure 2), then disengage each of the coils from the vacuum vessel segment on a specially designed stand fixture (Figure 3). As each cased TF coil was removed from the stand, it was placed on the table of a Marvel band saw located in the TFTR Test Cell (Figure 4). Since an individual TF coil was considered too large for transport to the Nevada Test Site for final disposal, each coil was cut into two segments at its mid-plane. From a test program perspective, this was an enormous benefit because it permitted the close visual examination of the four faces of the mid-plane cross section of every coil. These observations provided the first ever glimpses of the quality and consistency of the Westinghouse manufactured coils. Figure 5, showing the TF #3 nose section as it was removed from the Marvel saw, is typical of what was found in these cross sections. Note that the cooling channels are filled with residual copper slivers from the sawing process. Also, discolorations on the metal surfaces are the striations from the cut, while the color variation in the insulation is the effect of the light on the various strips and layers of material rather than any inconsistency in manufacturing.

Upon closer visual inspection, the coil bundles appeared to be in outstanding condition, showing virtually no observable signs of wear or fatigue. Epoxy and potting compound penetration appeared to be uniformly excellent throughout. No visible voids could be found. It was hard to imagine that a structure this complex could have endured over 100,000 mechanical and thermal load cycles and looked so pristine. When the case components were removed from the coil bundles, concerns about the deterioration of the potting compound on the exterior faces of the coil bundles proved to be unfounded. It had been suspected that with years of load cycling, coil movement within the case could have gradually cracked and ground the potting compound into small pieces or even dust. In fact, in every coil examined, the potting compound was not only found to be intact, but retained an almost Teflon-like quality (Figure 6) enabling the coil to glide in a nearly frictionless manner within the coil case during operations. When the case pieces were first unbolted, these segments, each weighing hundreds of pounds, could be readily slid along the coil's potting compound surface with relative ease (Figure 7). The only signs of wear were superficial cracks along the potting compound surface (Figures 8 & 9). There was no spalling. Black marks found on the surface of the potting compound was determined to be residue of the parting agent (mold release) used to prevent the potting compound from bonding with the case during original impregnation. The same black markings were found on the case pieces as well.

These visual inspections of every TF coil cross section found that the coils were built and assembled with remarkable consistency and quality. The extruded cooling channels were clear and clean. Turn transition regions were smooth and consistent (Figure 10). No evidence of any turn-to-turn shorts, burn marks or contact could be found. There were only two observable geometric anomalies. Occasionally, the turns within a 22-turn pancake would not be in perfect alignment and would vary by up to 3 mm (Figures 11 & 12). Also seen in these figures is that the turn-to-turn insulation layer thickness normally varied within a range of twenty percent of the 0.05-inch design thickness, but in no instance was any metal-to-metal contact observed.

As indicated previously, the baseline test program would take samples from TF coils #3 and #18. Accordingly, these coils were to be cut differently, in accordance with the layouts shown on Figures 13 & 14, respectively [Reference 7]. Three two-to-three-foot long segments would be taken from each of these coils (Figure 15). Segments from the mid-plane inner and outer legs of these two coils would be set aside. TF #3's third segment would be the water-fitting region while TF #18's third segment would be from the lead block region. Six cuts on the Marvel saw were required for each of these coils instead of the usual bisecting two cuts for the other TF coils (Figure 16).

The D&D staff working in the TFTR Test Cell were alerted to observe the TF coils for anything that seemed different or unusual. They observed and reported that TF coil #8 was different. Up to TF #8, which was cut after TF's #3 & 18, each cut of a TF coil on the Marvel saw averaged 5 to 6 hours. This included cutting through the entire coil and case cross section. Early on, cuts were taking even longer because cutting through the Inconel 718 case bolts added a significant amount of time. Recognizing the bolt issue led to a policy of removing all bolts along a cut line in order to expedite the process. The first cut of TF #8 took approximately one hour. Close examination of the cutting procedure indicated that the saw band speed was slower, but the usual procedure had been followed otherwise. Given the unusual circumstances, it was decided that a small section of the TF #8 nose was to be set aside for material testing (Figure 17). The second cut to remove this segment took longer than one hour, but with the slower band speed, still took far less than the average 6 to 8 hours. All TF coil cuts from that point forward were made at the slower band speed and the average cut time dropped to 2.5 to 4 hours each, but none came anywhere near the one hour it took for the first TF #8 cut. This anomalous event justified the closer examination that followed for TF #8. Saw blade quality was another possible variable that may have influenced the cut time. Normally, a new saw blade was used for every TF coil cut made during the D&D program. It was possible that the blade used for the first TF #8 cut was of exceptional durability and sharpness. Regardless, TF #8 was to be part of the material test program along with the segments cut from TF #3 and #18.

In all, seven TFTR TF coil sections were set aside for physical and metallurgical testing, the aforementioned six sections from TF #3 and #18, and the nose section from TF #8. The cases of the three nose sections (TF #3, 8, 18) and two back leg sections (TF #3 and 18) were disassembled in the TFTR Test Cell. While on a pallet and properly supported with slings, each of these five sections had its case bolts removed. The four Nitronic case sections (inner ring, outer ring, and two sidewalls) were saved, along with the bolts and shims for each section (Figure 18). All parts were cataloged and retained for further inspection and testing. Coil and case segments were decontaminated and measured by HP for activation. Following decontamination, activation levels in the disassembled sections were measured as follows:

Copper	1.5 +/- 0.5 mrem/hr - contact 0.5 +/- 0.2 mrem/hr - @ 30 cm
Nitronic 33	2.8 +/- 0.5 mrem/hr - contact 1.2 +/- 0.3 mrem/hr - @ 30 cm
Insulation	Measured with copper, but activation should be less than copper

Once this process was complete, the pallet for each coil segment was transported to the Rad Waste building. The other two cased coil segments (water fittings on TF #3 (Figure 19) and lead block on TF #18 (Figure 20)) were sent intact to the Rad Waste building. Due to the various protrusions from the sidewalls of these segments, their disassembly would be a more delicate operation involving removal of external insulation and potting material with a router first. This work was to be done in the Rad Waste building where the work could be performed with fewer distractions. The level of activity and premium placed on available floor space in the TFTR Test Cell made it impractical to attempt this effort there. The Nitronic case sections surrounding the TF #3 water fitting section (Figures 21 & 22) and the TF #18 lead block section (Figure 23), were successfully disassembled in the Rad Waste building shortly thereafter. All disassembled case segments were kept on individual pallets along with their corresponding coil sections in the Rad Waste building until individual pieces were required for test specimen preparation in the RESA building machine shop. In this way, a minimum of activated material would be outside of the Rad Waste facility at any given time.

The TF #3 water fitting coil section was originally cut in the TFTR Test Cell to ensure that the fourteen water fittings would remain intact. Some of the fitting protrusions had been cut off during diamond wire cutting, but all of the braze joints and portions of the outside tubes needed for the metallurgical investigation were still intact. Ultimately, this coil section was disassembled turn by turn in the RESA building so that individual water fittings could be subjected to the necessary testing.

The TF #18 lead block segment was originally cut in the TFTR Test Cell to preserve both the lead block protruding from the side of the coil as well as the lead spur located within the coil body. Over the years, the lead spur had been identified as the prime candidate for the origin of the chronic leak in TF #18 (Figure 24). While still in the Rad Waste building, the lead area was borescoped from several locations, but the results were inconclusive regarding the origin of the leak. It was originally planned to disassemble this coil section so that the lead block/spur turn could be investigated in detail, however, resources became limited and this exercise could not be completed. The TF #18 lead block coil section remains in the Rad Waste building awaiting the possibility of conducting this investigation at some point in the future.

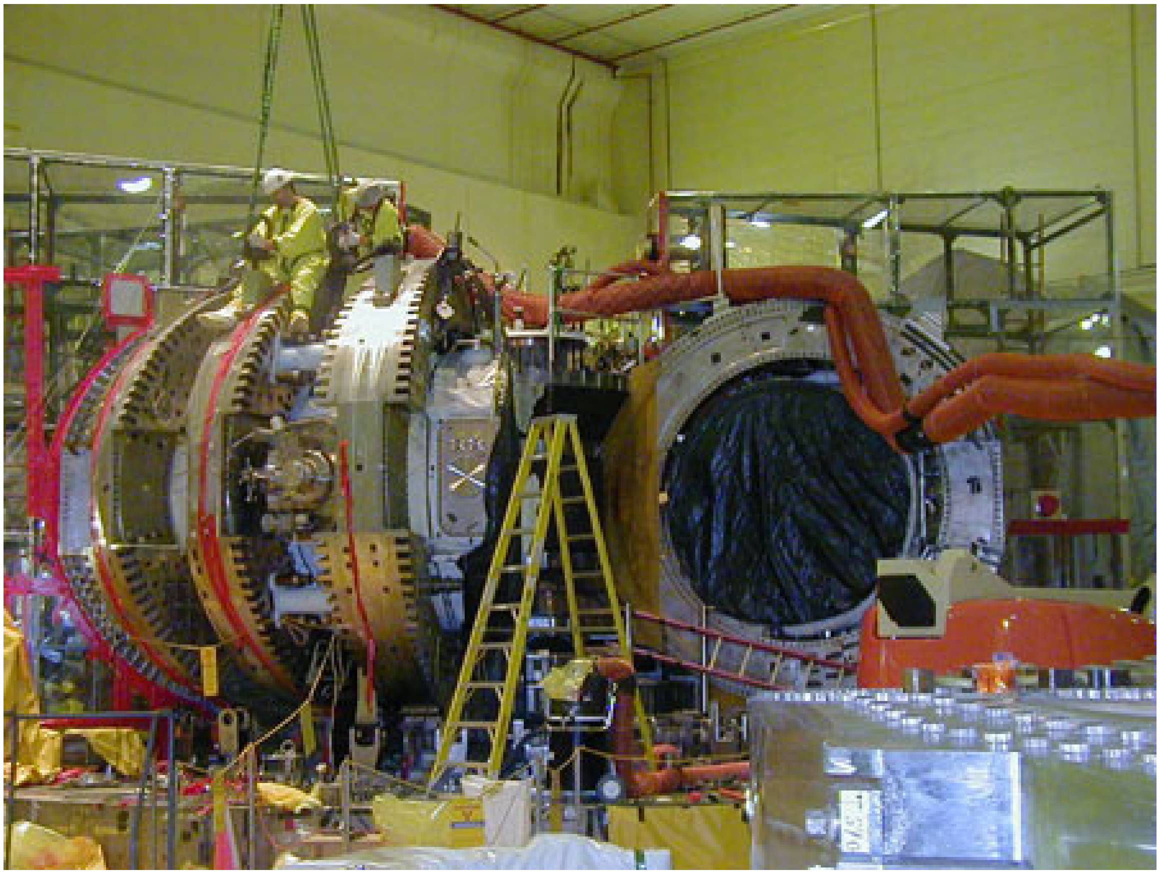


Figure 1 - Removal of a TFTR two-coil segment from the pedestal

Figure 2 - Diamond wire cutting of TFTR

Figure 3 - Two TF coil segment on stand fixture

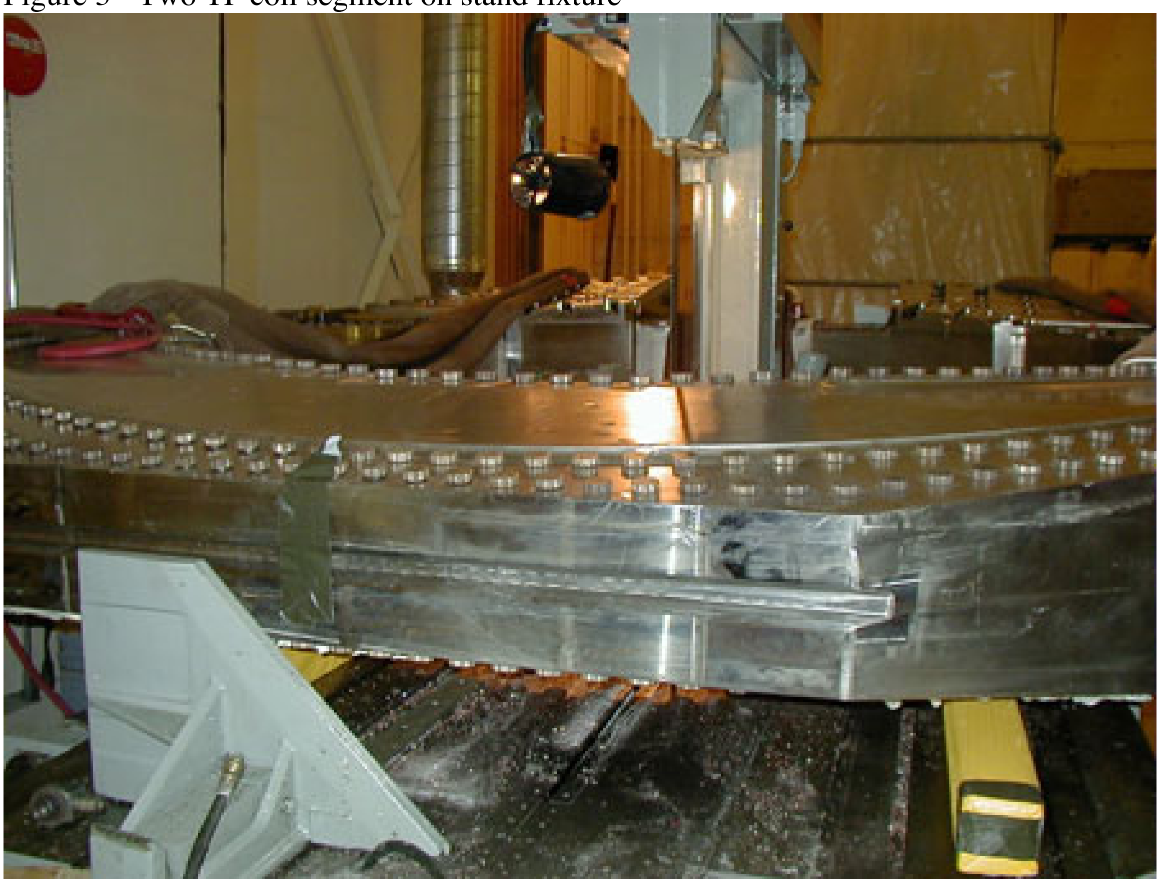


Figure 4 - Marvel band saw preparing to cut TF #3 nose section

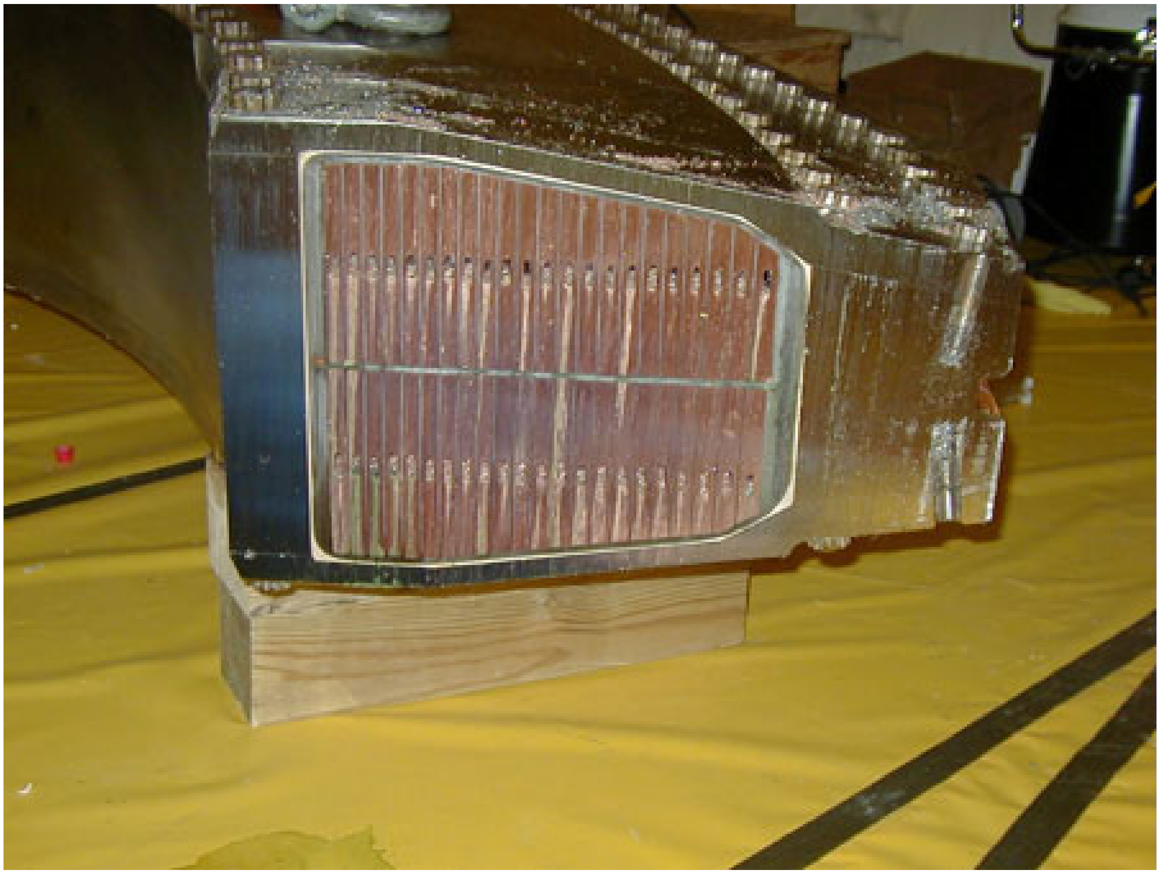


Figure 5 - TF #3 nose section following saw cut


Figure 6 - TF #3 nose section bundle with potting compound intact

Figure 7 - Inner and outer ring case sections on TF #3 back leg coil bundle

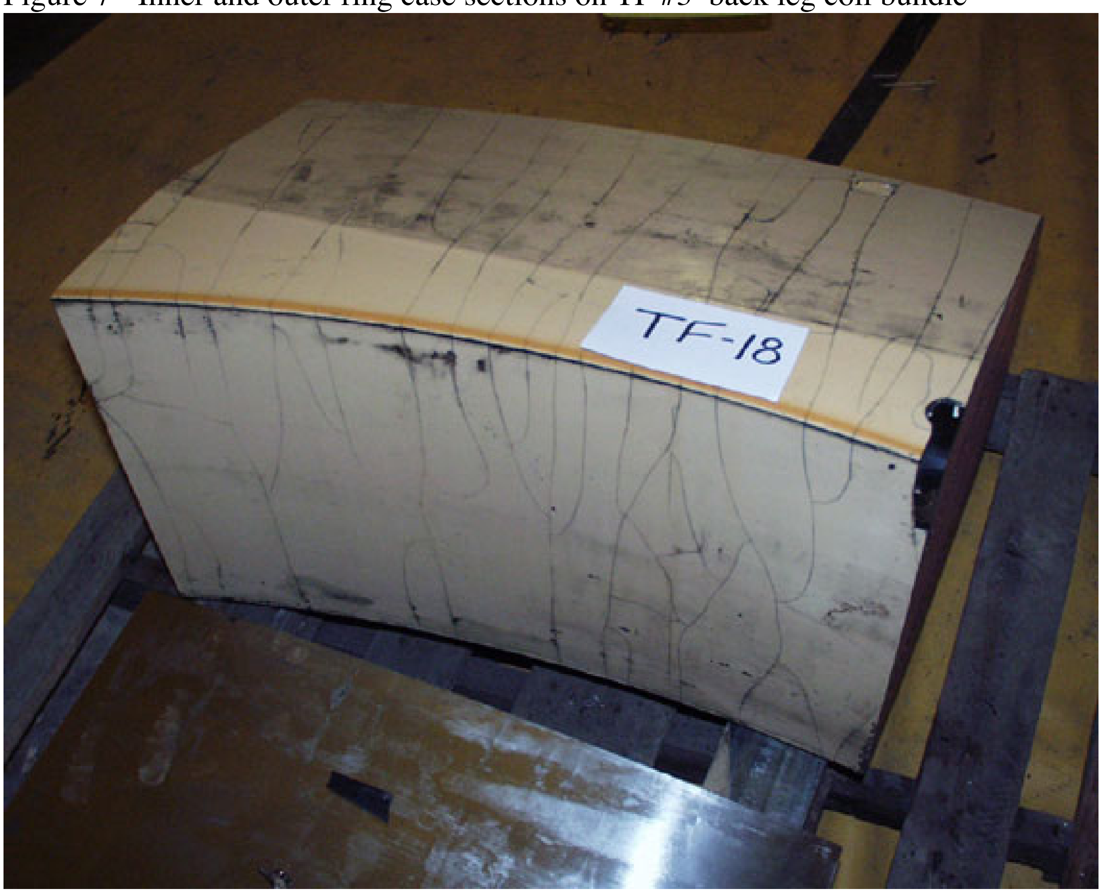


Figure 8 - Minor cracking in TF #18 nose section potting compound

Figure 9 - Minor cracking in TF #18 back leg section potting compound


Figure 10 - Close up view of turn transition in back leg of TF #3

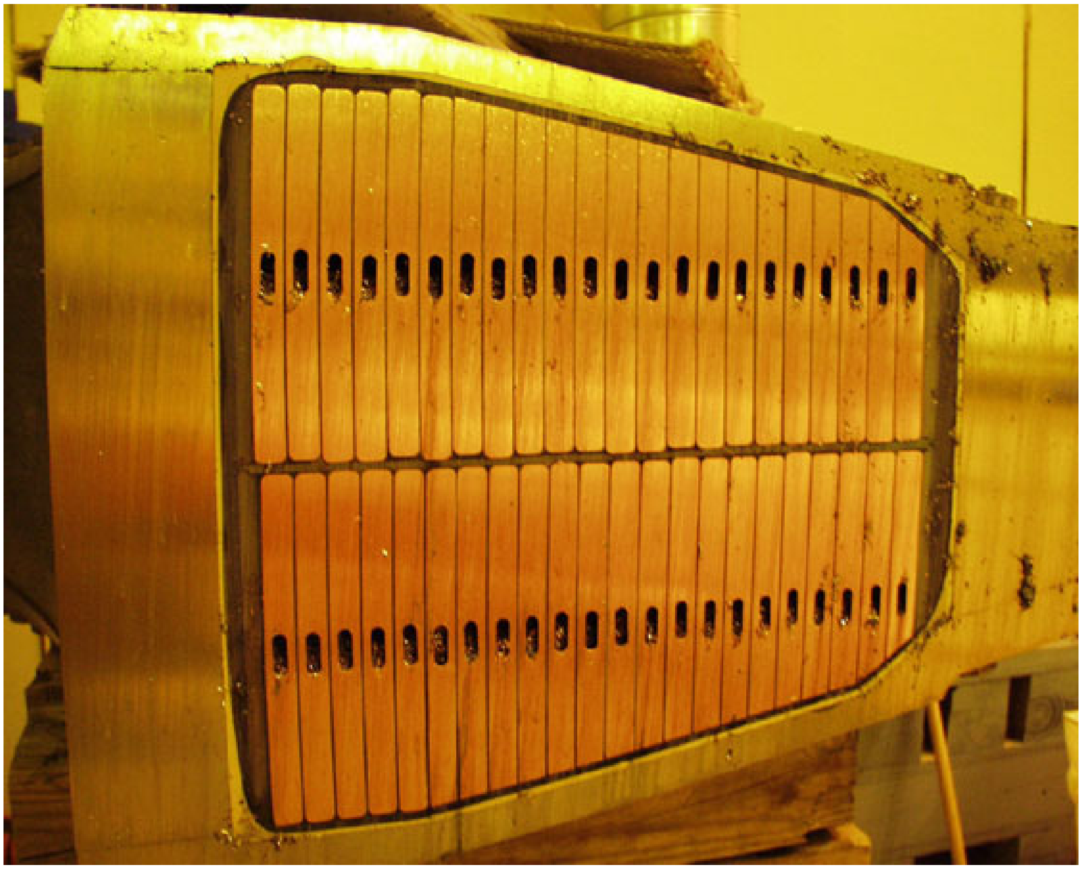


Figure 11 - Slight turn-to-turn misalignment

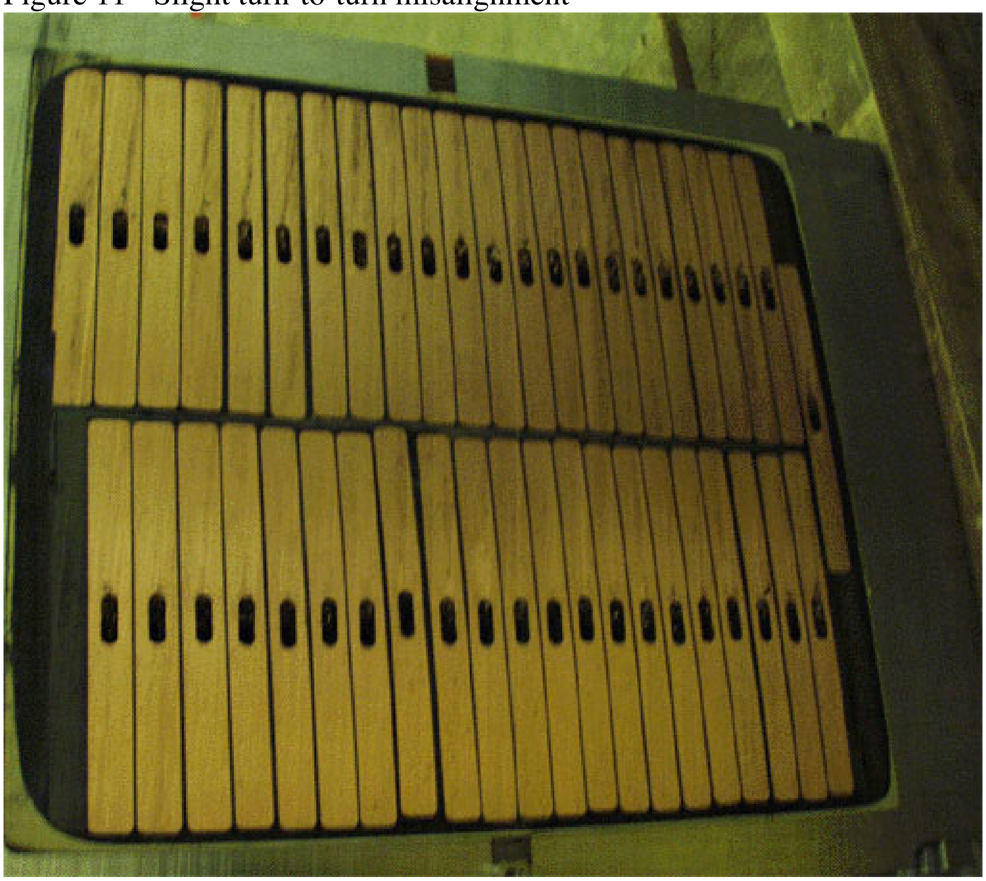
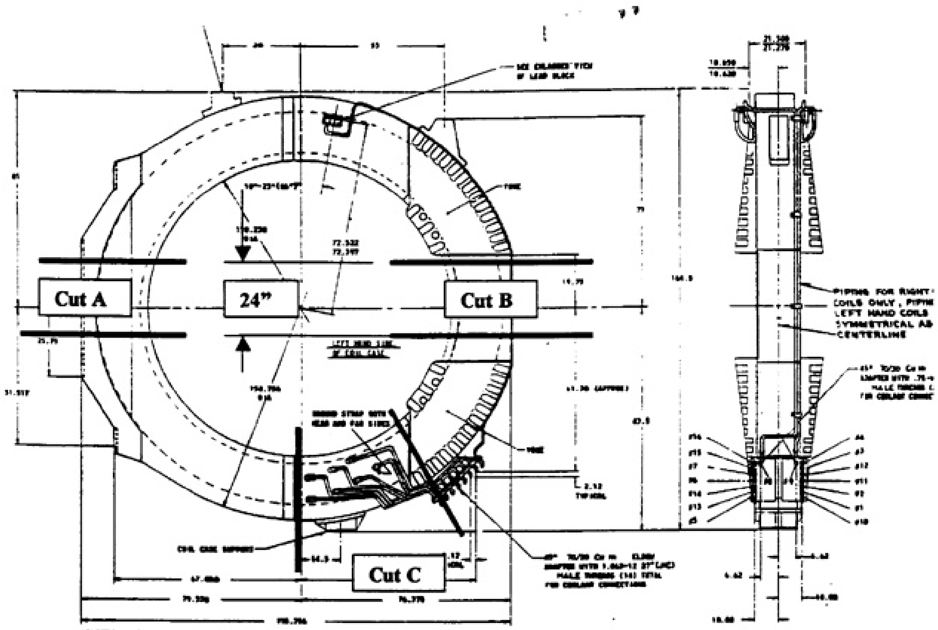


Figure 12 - Slight turn-to-turn misalignment

D-D&D-IP-2633 Rev.0
Dissection of TF Coils for Engineering Examination and Analysis

TF LOG SHEET NO. 1 ……………… *TF-3 (Westinghouse No. 255)*



Cut A -Inner Leg (approx. 24 inches in width) **(Lead Tech. Signoffs)**
Cut Complete: ________________ **Date:** _______ Disassemble TF Segment: ________________ Date: _______
Observations:

Cut B -Outer Leg (approx. 24 inches in width) **(Lead Tech. Signoffs)**
Cut Complete: ________________ **Date:** _______ Disassemble TF Segment: ________________ **Date:** _______
Observations:

Cut C –Fitting Area (approx. 3 inches either side of lower fittings) **(Lead Tech. Signoffs)**
Cut Complete: ________________ **Date:** _______ Disassemble TF Segment: ________________ Date: _______
Observations

Controlled Copy

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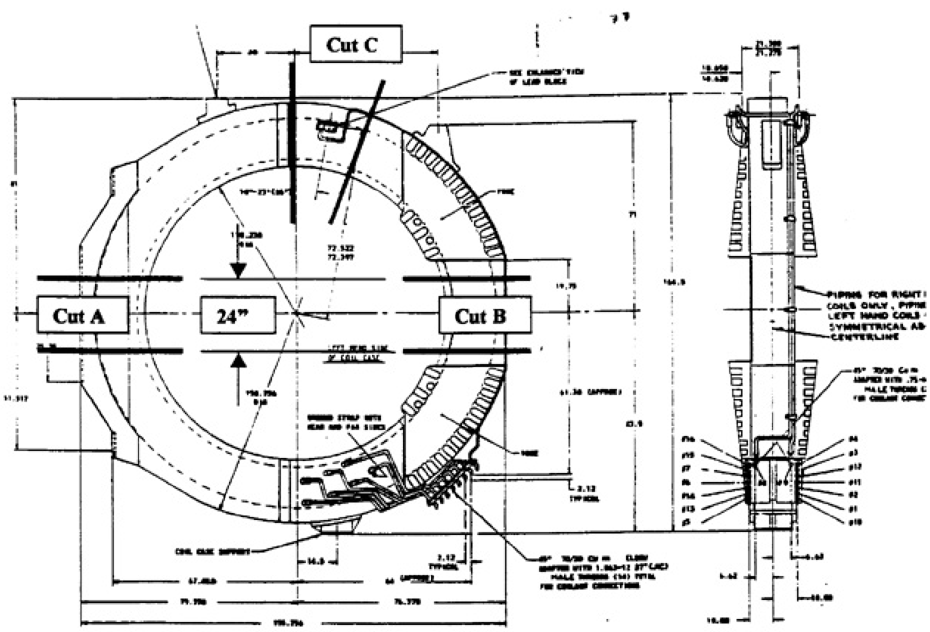
Figure 13 - Cut plan to extract three test sections from TF #3 [Reference 6]

D-D&D-IP-2633 Rev.0
Dissection of TF Coils for Engineering Examination and Analysis

TF LOG SHEET NO. 2 ……………….*TF-18 (Westinghouse No. 258)*



Cut A -Inner Leg (approx. 24 inches in width) **(Lead Tech. Signoffs)**
Cut Complete: ________________ **Date:** _______ Disassemble TF Segment: ________________ **Date:** _______
Observations:

Cut B -Outer Leg (approx. 24 inches in width) **(Lead Tech. Signoffs)**
Cut Complete: ________________ Date: _______ Disassemble TF Segment: ________________ Date: _______
Observations:

Cut C –Terminal Block Area (approx. 8 inches either side of terminal block) **(Lead Tech. Signoffs)**
Cut Complete: ________________ **Date:** _______ Disassemble TF Segment: ________________ Date: _______
Observations

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Figure 14 - Cut plan to extract three test sections from TF #18 [Reference 6]


Figure 15 - Encased TF #3 back leg section prior to disassembly
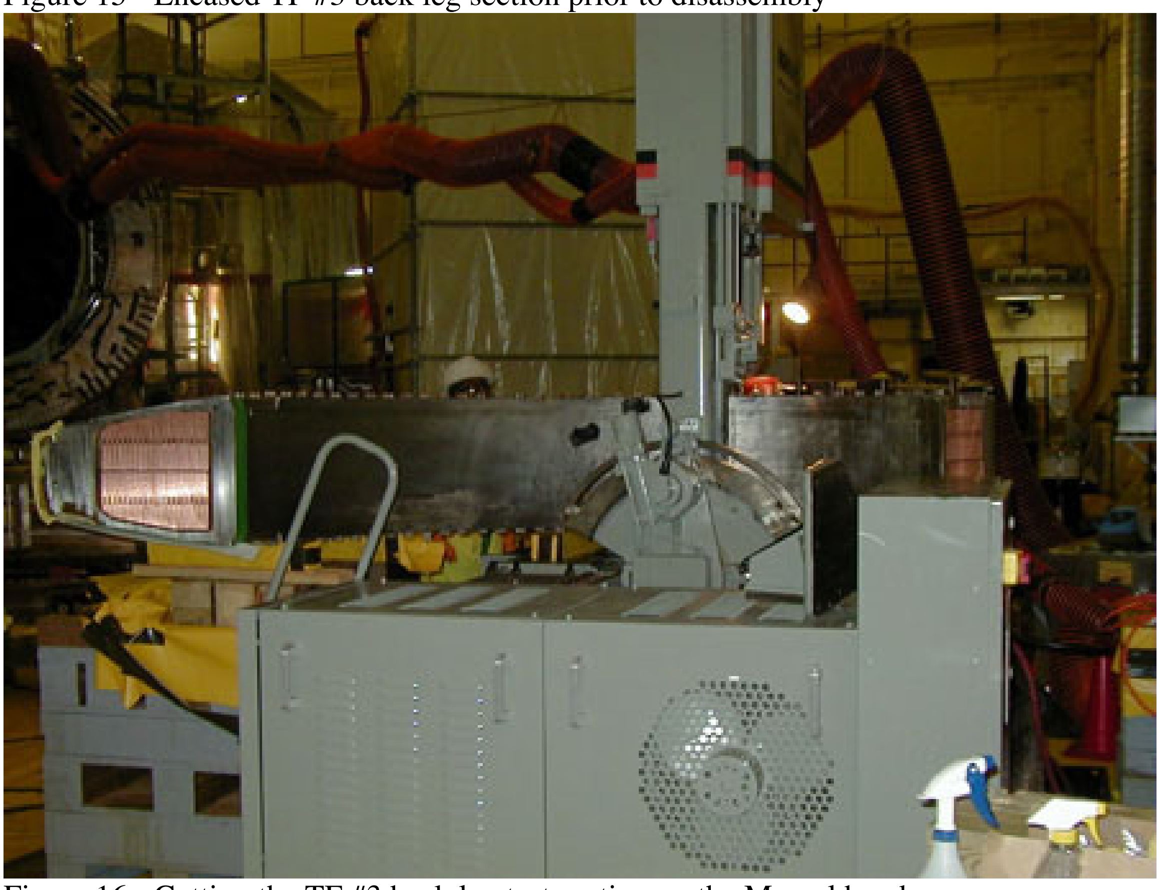
Figure 16 - Cutting the TF #3 back leg test section on the Marvel band saw

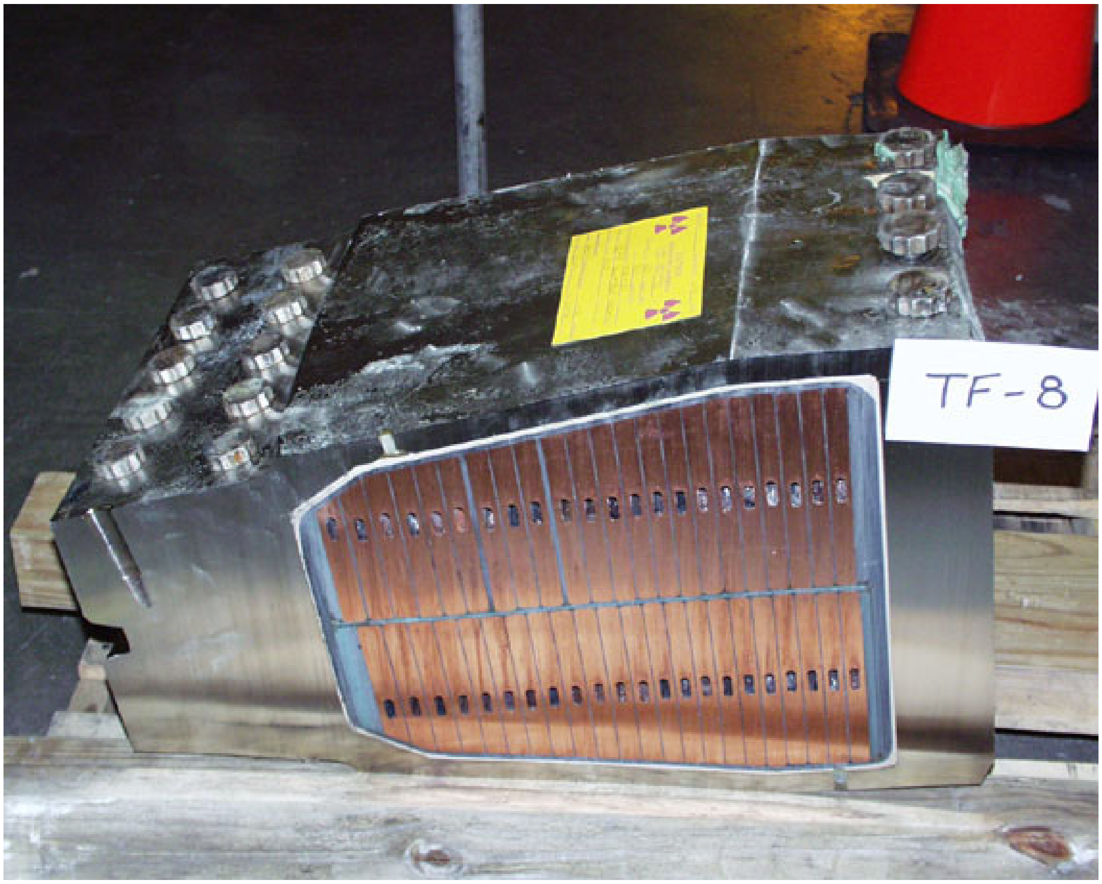

Figure 17 - TF #8 nose section

Figure 18 - Bolts and shims following TF #3 back leg coil case section disassembly

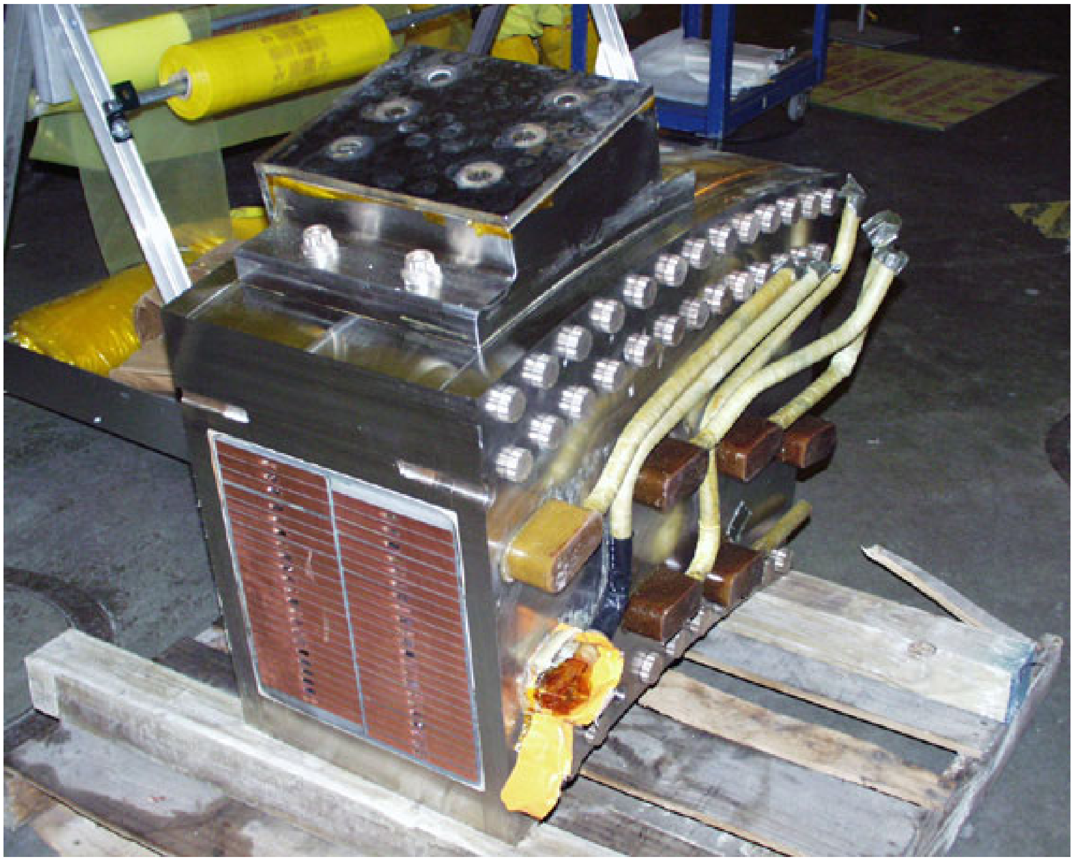
Figure 19 - TF #3 water fitting coil section
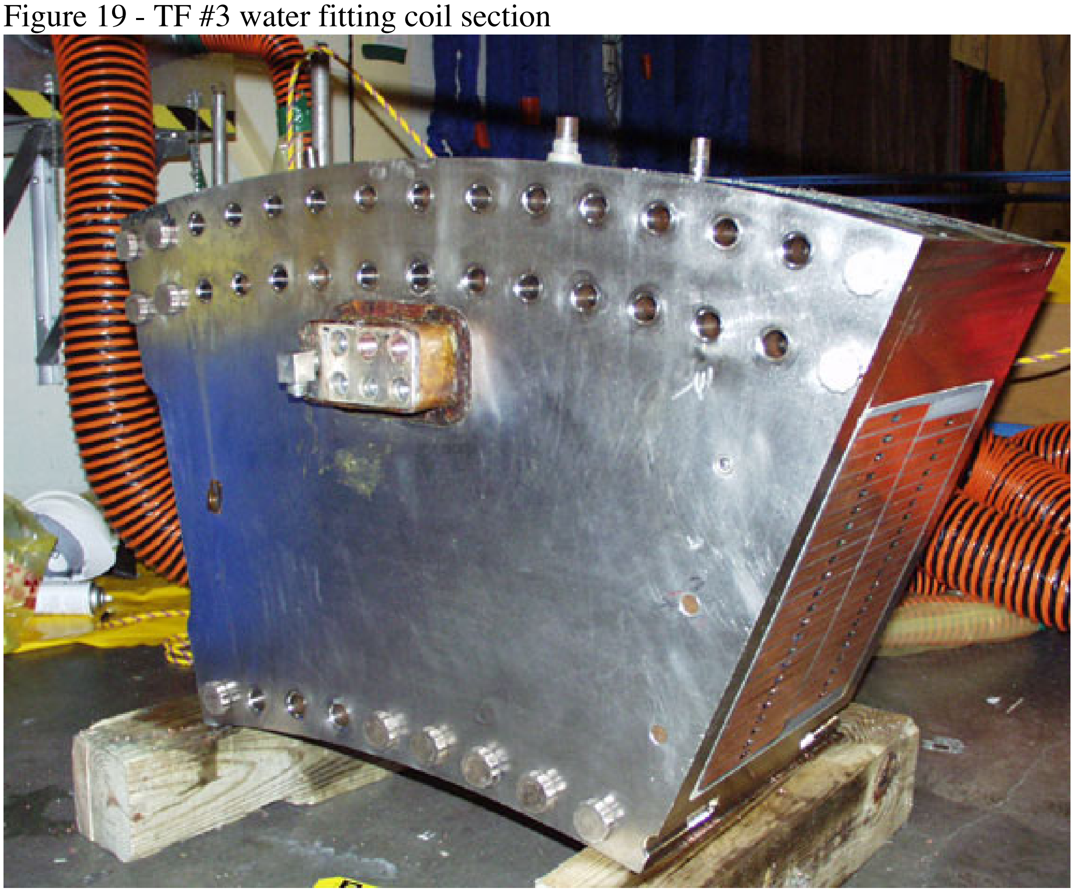
Figure 20 - TF #18 lead block coil section

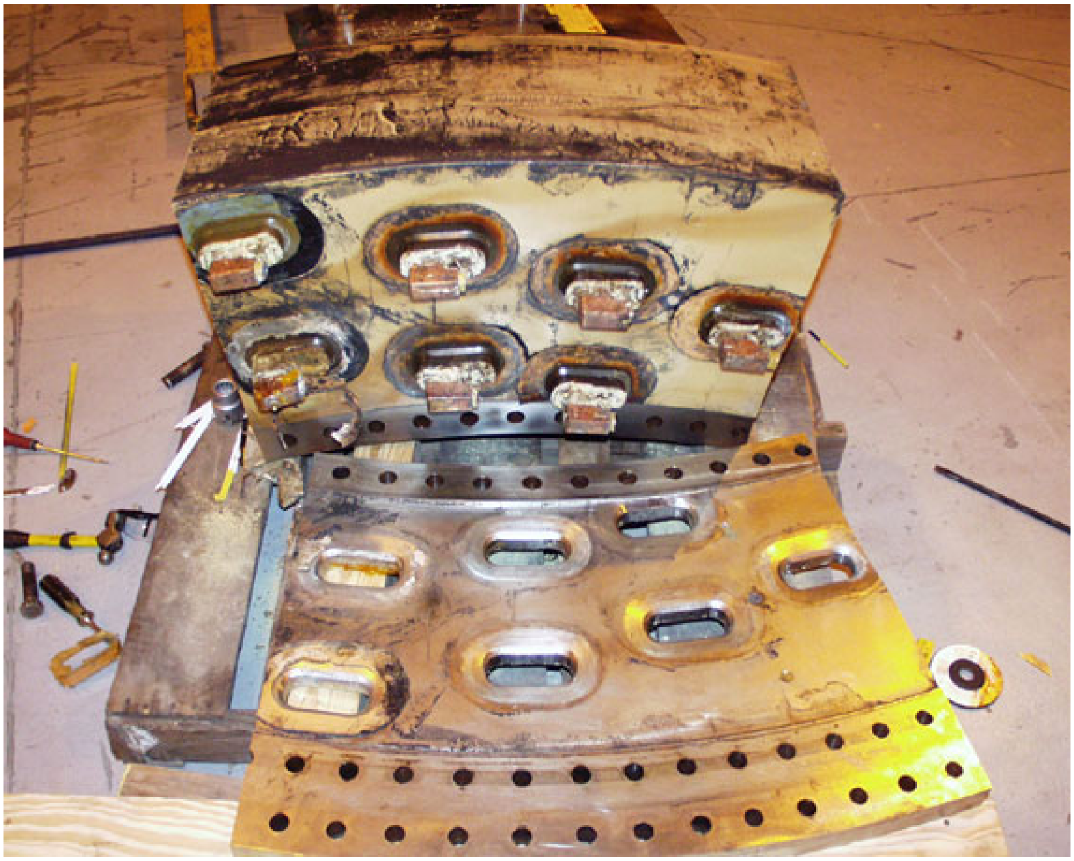
Figure 21 - Disassembled TF #3 water fitting coil section
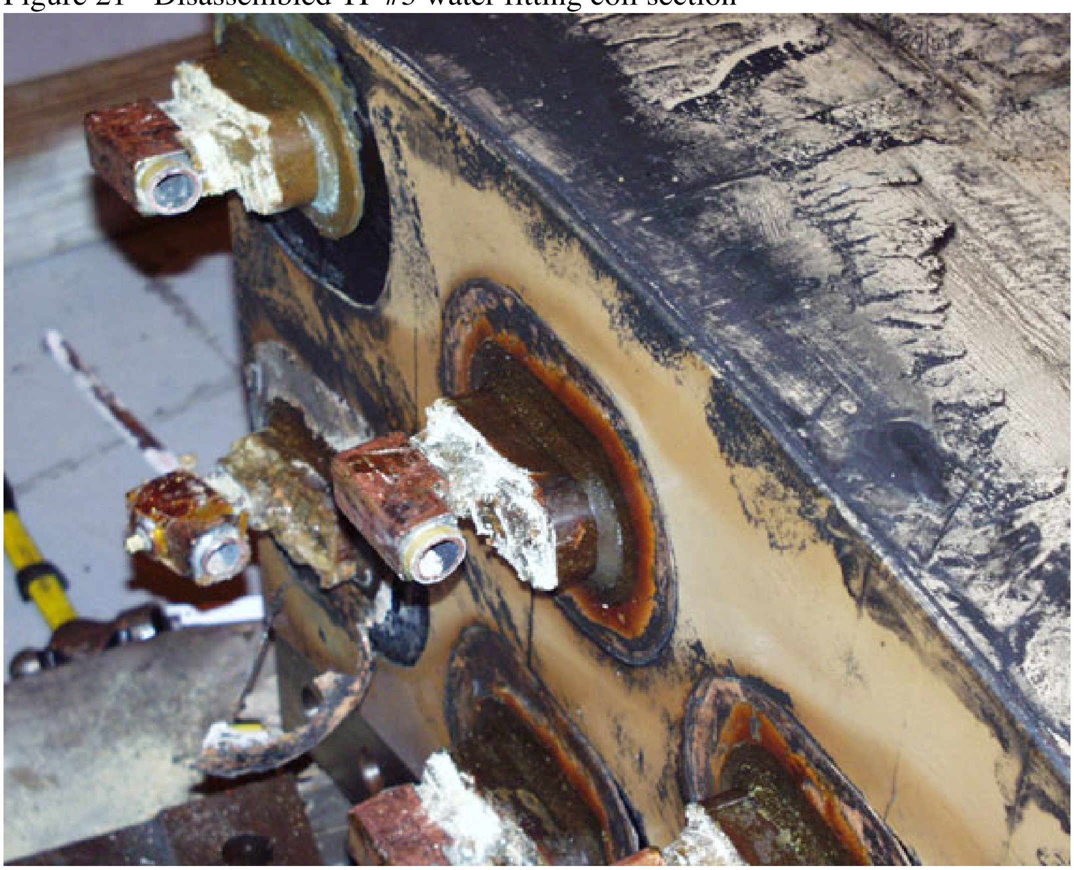
Figure 22 - Close up of TF #3 water fittings with partial removal of insulation

Figure 23 - Close up of TF #18 lead block

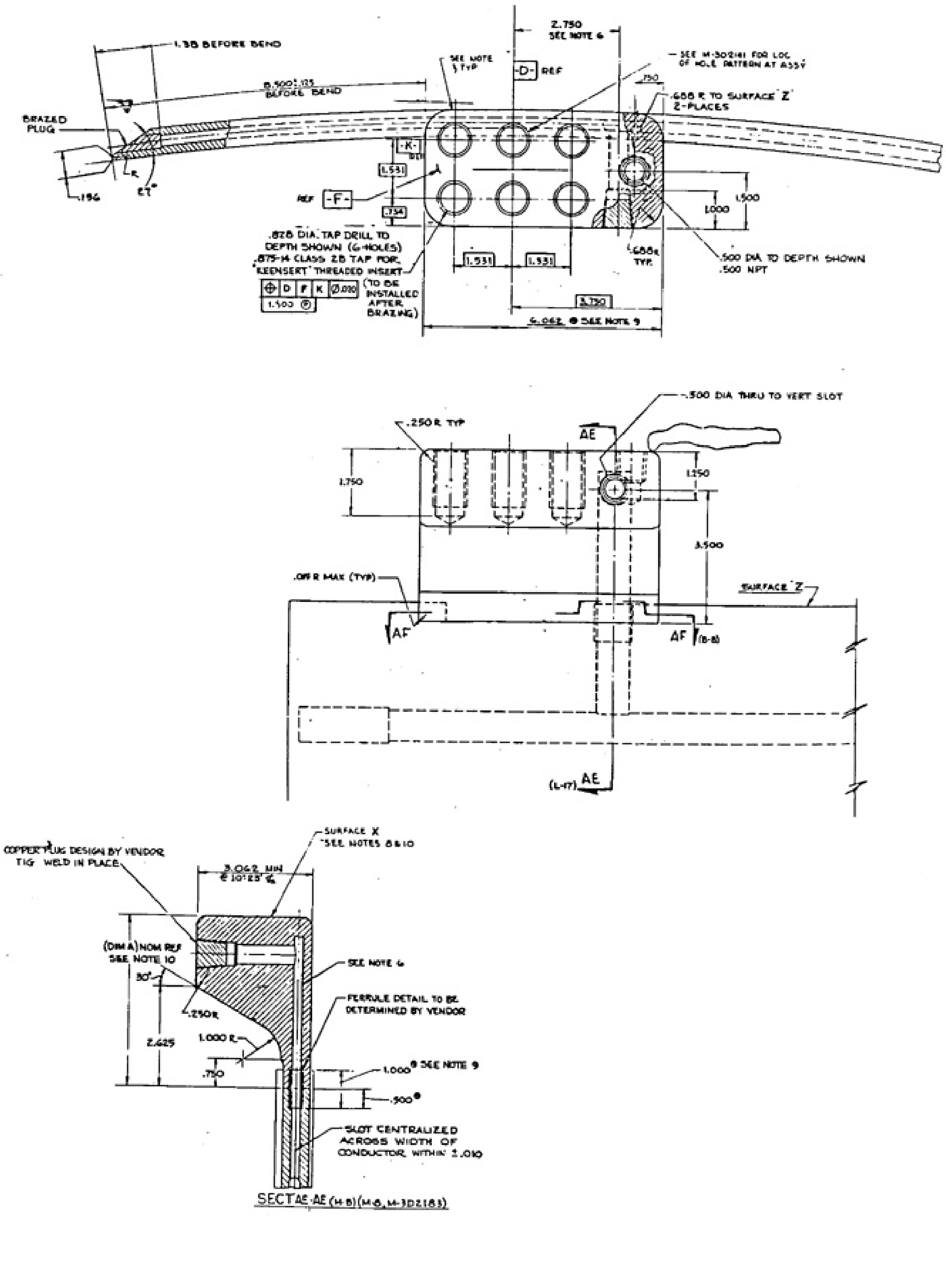

Figure 24 - Schematic of a Typical Lead Block and Lead Spur Reg

3b. COIL BUNDLE DISASSEMBLY AND TEST SPECIMEN PREPARATION

Once a Radiological Controlled Area (RCA) was set up by Health Physics (HP) in the RESA building to use as a holding area, individual coil and case pieces were transported from the Rad Waste building on an as needed basis. RCA's were set up around machines to be used for cutting and milling test specimens.

Mechanical testing of the OFHC copper from the coil bundles and the Nitronic 33 from the coil cases were comprised primarily of two ASTM standard tests - ASTM E8 ("Standard Methods of Tension Testing of Mechanical Materials") and ASTM E23 ("Standard Methods for Notched Bar Impact Testing of Metallic Materials") [Reference 8]. Conformance with the ASTM E8 tension testing would require precision cut 'dog bone' type specimens (Figure 25). Similarly, precision cut Charpy impact (notched bar) specimens (Figure 26) would be required for the ATSM E23 tests. All specimens were prepared by PPPL's machine shop in the RESA building.

It is important to note that the importance of following the ASTM standards is to give the tests credibility and validity for the purposes of publishing results and comparing with data available in the literature. The ASTM is the recognized international testing standard reference.

Data obtained from the tension test can provide the yield, ultimate, modulus of elasticity, reduction of area, and elongation of a material. The impact test provides a standardized value of impact energy to failure that can give insight into the relative ductility and fracture characteristics of a material.

It was readily apparent that the sidewalls would be best suited for cutting the test coupons based on the geometry of the four coil case pieces for each disassembled coil segment (inner ring, outer ring and two sidewalls). The principle reason for this decision was that every dimension of the inner and outer ring pieces was at least several inches. A great deal of machining would be necessary to cut test coupons from these thick pieces. On the other hand, the sidewall thickness varies roughly from 0.75 inches to 1.5 inches (Figure 27). It is worth noting that Nitronic 33 is so difficult to machine that one machinist at first thought that he was cutting an Inconel alloy. Machining the sidewall plates into the necessary tension and impact test articles would greatly simplify the preparation process saving a substantial amount of time and manpower.

Furthermore, it was decided that the most efficient way to machine the required 'dog bone' shaped tension specimens was with the water jet cutter because of the difficulty of machining Nitronic 33 (even in the thinner sidewall plates) with a conventional blade saw. Charpy impact test specimens, however, were still prepared by more conventional methods because of their simpler geometry and smaller size.

A minimum of three tension and three Charpy specimens were cut in each of two perpendicular directions from the sidewall plates of the three TF coils that were set aside (#3, 8, and 18). Specimens were cut oriented along the two principal plate directions –

TFTR's poloidal direction and minor radial direction. Depending on the procedures that were used to build the coil case sidewalls, the material properties might be affected by plate orientation. The testing would determine this.

While the Nitronic 33 material from the sidewall plates was readily accessible but difficult to machine, the OFHC copper was exactly opposite. Working with the 44-turn bonded copper bundles was fairly cumbersome and time consuming. Machining the copper was relatively easy once it could be extracted. First, the two 22-turn pancakes had to be separated from each other. This was usually accomplished by setting the overall bundle in a sling to orient it for a single saw cut in the RESA building. Once to two pancakes were separated, the next task was to separate the 22-turns in each of the pancakes from each other. This required the removal of the potting compound and overwrap materials from the pancakes, to be followed by the turn-to-turn separation of the copper. Several randomly selected turns of copper were chosen beforehand to be extracted for cutting into the tension and Charpy test coupons. Figure 28 shows a typical turn of copper with portions of insulation tape still attached to the turn. Each one of these selected turns would then be cut in such a way as to yield three coupons in both the axial and transverse directions for impact testing (six impact test coupons from each selected turn). Figure 29 shows a typical Charpy coupon prior to machining. This was accompanied by cutting three tension coupons (Figure 30) from each selected turn along the axial (poloidal) direction of the turn. Acceptable tension specimens in the transverse direction were not possible because of the presence of the extruded cooling channel in the turn. Figure 31 shows the leftover turn following the cutting of all necessary coupons from it.

The process of separating the copper tuns from their pancakes furnished extremely valuable information about the turn-to-turn bond strength between the copper and epoxy. This bond strength was one of the most debated issues during the days of TFTR operations because it led to the calculated TF coil stiffness and strength. This ultimately determined the limits for coil currents and magnetic fields. The question was could the coil bundle be assumed to be fully bonded resulting in a composite cross section of maximum stiffness, or was there any turn-to-turn delamination resulting in a lower stiffness cross section where only friction kept adjacent turns from sliding relative to each other? To be conservative, analytical models of TFTR assumed some degree of delamination.

The visual inspection of the coil bundles, as seen in prior figures and close-up in Figure 32, gave every appearance that the coil was fully bonded because of the pristine condition of the copper, insulation material and epoxy. There were frequent instances during actual turn-to-turn separation where the turns were indeed well bonded and were extremely difficult to pry apart. But there were also instances where the pancake turns separated with significantly less effort. In fact, in some instances, the turns separated with hardly any effort with the epoxy bonded to only one copper turn. In other cases, the epoxy and insulation apparently failed to bond to either adjacent turn. The copper turns gave every appearance of proper pre-treatment and the integrity of the epoxy and glass tape layer was observed, yet turn-to-turn bonding either never occurred or did not persevere satisfactorily possibly because the pre-treatment was not properly applied or was not an effective process. For example, in Figure 33 the glass fiber tape, which should be bonded to the copper via epoxy, can be seen to be substantially delaminated from the turn. In a more extreme example, Figure 34 is a sleeve of bonded glass fiber tape where the copper turn simply slid out. Figure 35 is an instance where the entire ground wrap insulation of a coil bundle 'popped' off the bundle with only minimal effort during turn separation. These observations of variable turn-to-turn and insulation delamination in the TF coil bundles is direct evidence that the structural assumption of a perfectly bonded and integral composite coil would have been unconservative, thereby justifying the design limits originally set during machine operations. Accordingly, the need to perform elaborate shear testing at this time to determine the turn-to-turn bond strength was considered moot because even where bonding occurred, the bond strength was inconsistent.

Another important observation made while the TF coil bundles were being separated was that several turns had visibly detectable brazed joints where the lengths of extruded copper were spliced to form the wound coil. Every inspected joint had a flawless appearance with no evidence of any wear or residual defect. Test specimens were taken from several of these braze joint regions.

Once the selected turns to be used for mechanical testing were extracted from the bundles, the test coupons were cut and machined into the ASTM specimens ready for testing. It was during this process that the machinists observed and reported that the degree of difficulty in machining and milling the copper varied from specimen to specimen. Some coupons cut more easily than others, indicating a softer, lower strength copper. Upon further inspection, it was found that the copper was softer in the immediate vicinity of the brazed joints. High temperatures encountered during the brazing process had locally annealed the copper, which gradually hardened as one moved away from the joints, as expected. The extent of this annealing would be determined by the mechanical tests.

There was one additional observation made during the dismantling of the outer leg coil bundles. A thin strip of copper, approximately one millimeter thick and approximately one inch wide, was found embedded between the outerwrap and potting compound of each coil bundle centered between the pancakes (Figures 36 & 37). This strip of copper is the ground plane electrode that electrically connected the coil's ground plane to the case.

Figure 25 - Typical 'dog bone' tension specimen

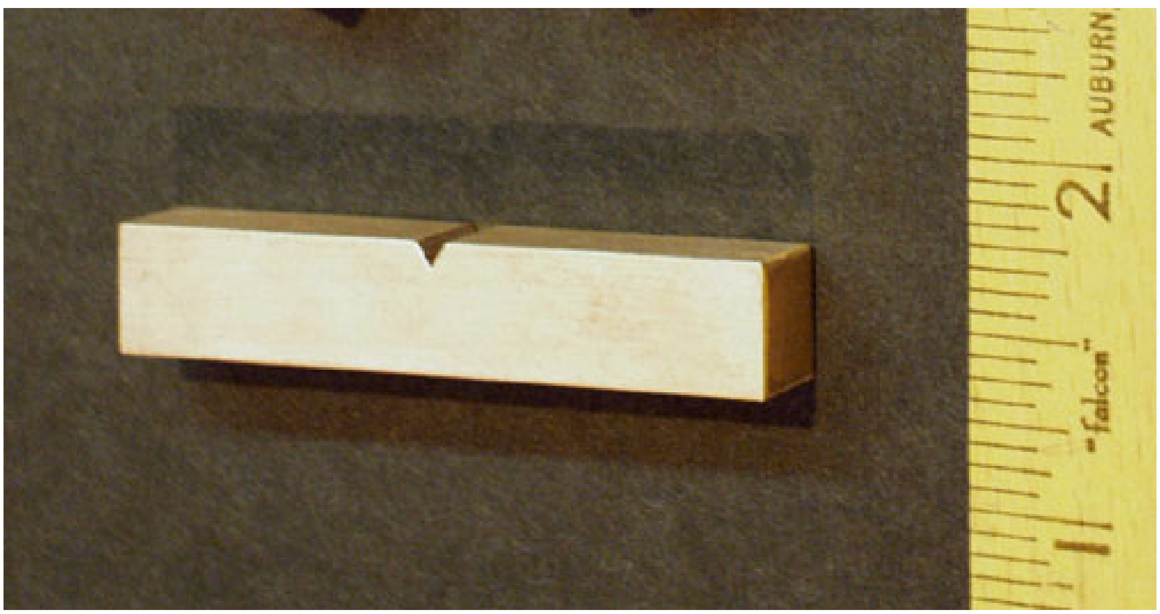

Figure 26 - Typical Charpy V-notch impact specimen

Figure 27 - Profile view of back leg sidewall case plates

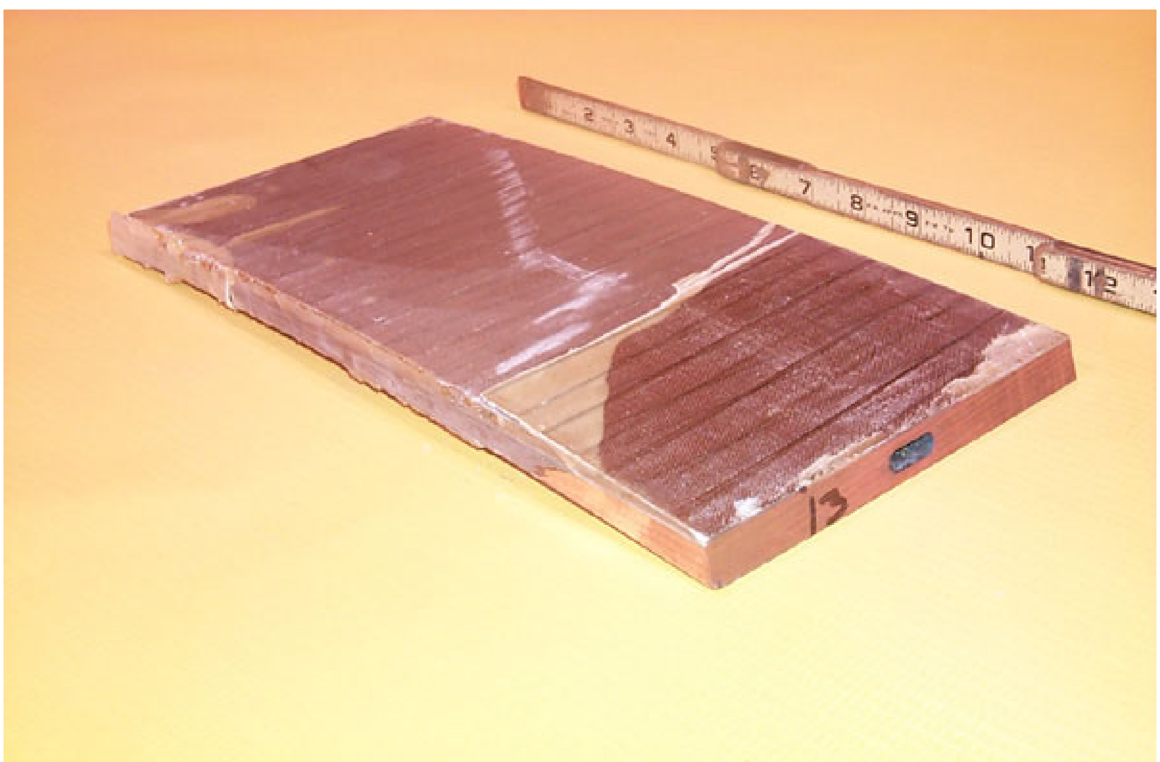

Figure 28 - Typical copper turn (with insulation tape) following bundle separation

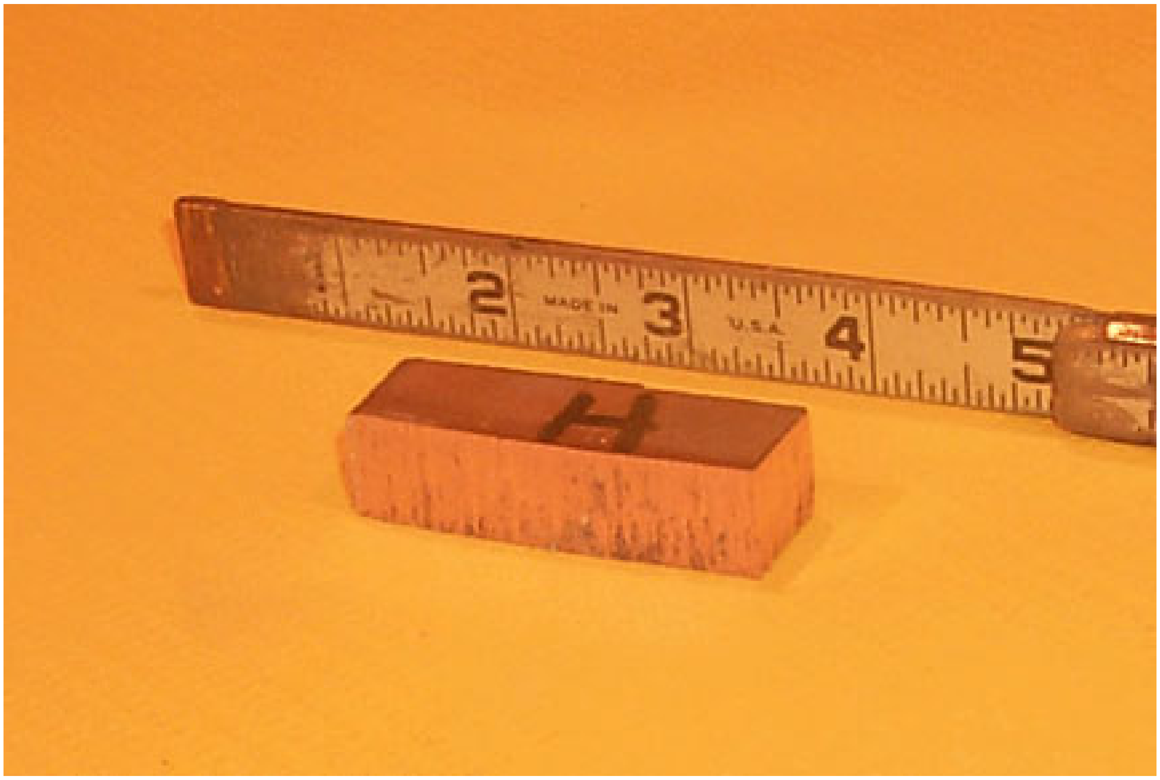

Figure 29 - Typical Charpy coupon cut from copper turn prior to machining

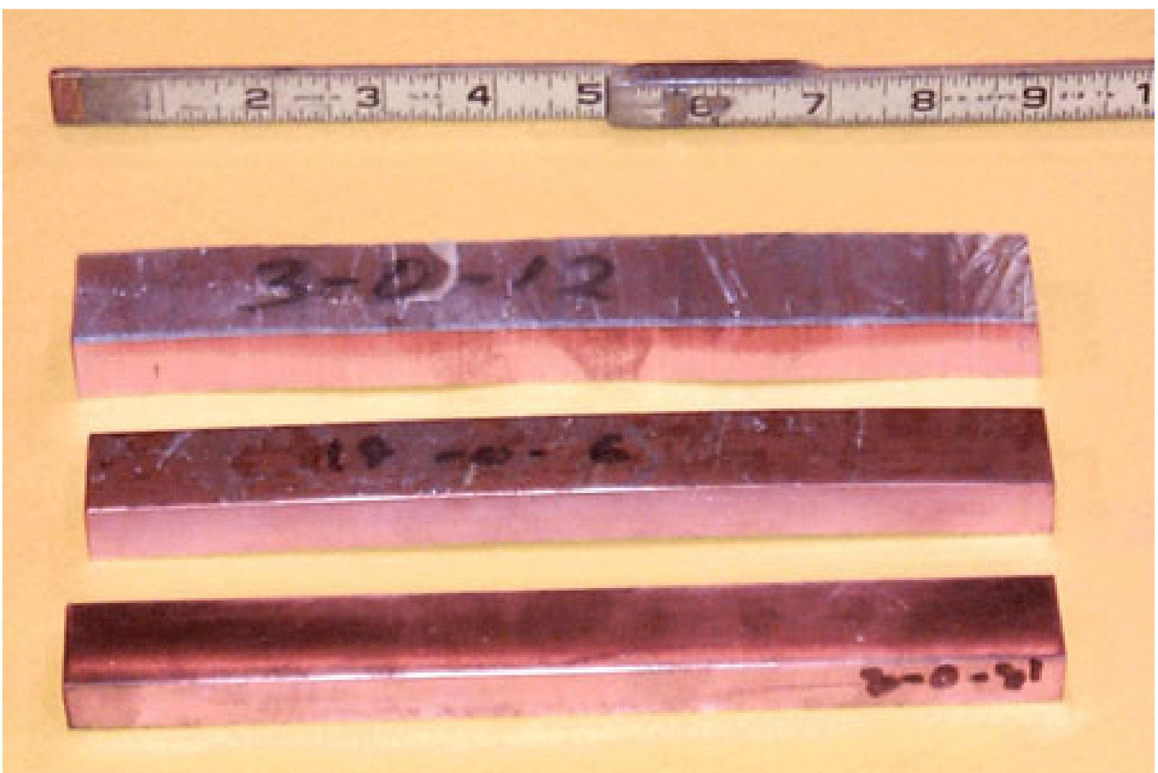

Figure 30 - Typical tension coupons shown in various stages of machining prior to 'dog bone' milling

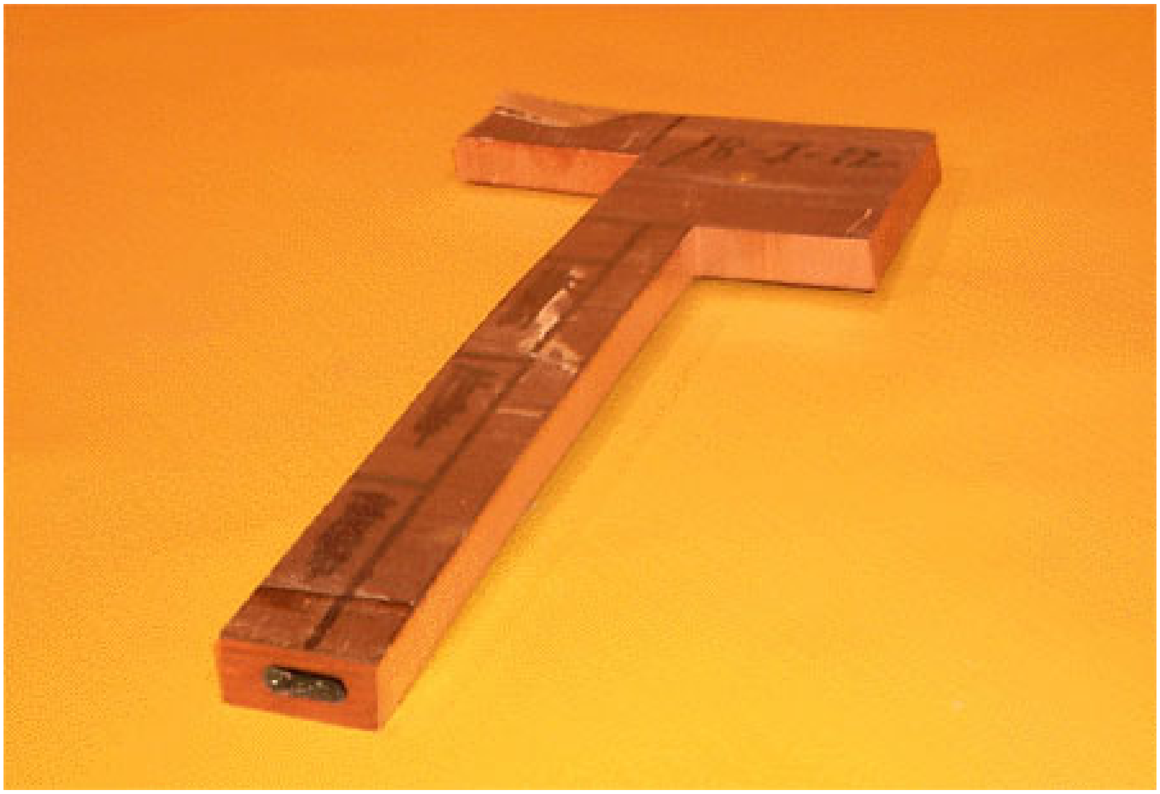

Figure 31 - Leftover turn following cutting of 6 Charpy and 3 tension coupons

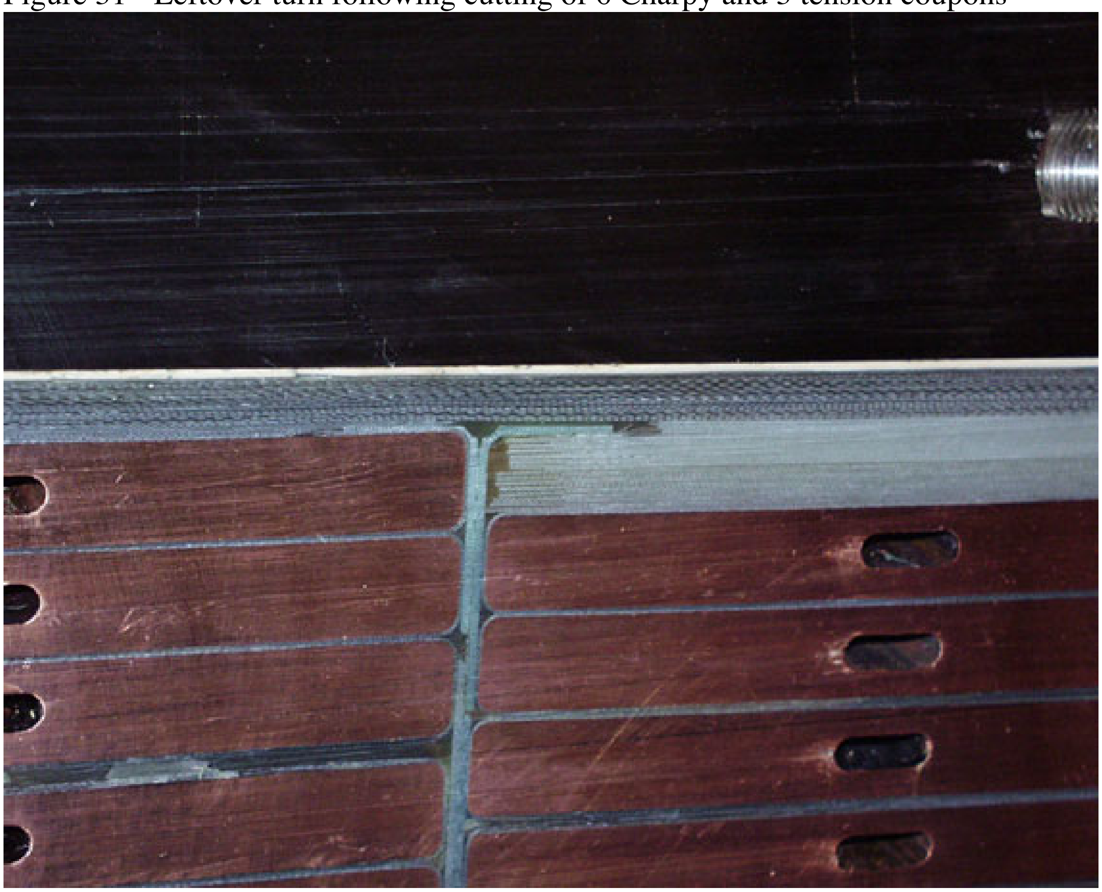

Figure 32 - Extreme close up of insulation where tape layers can be distinguished

Figure 33 - Bonded tape delaminated from copper turn

Figure 34 - Sleeve of bonded glass fiber tape where copper turn slid out

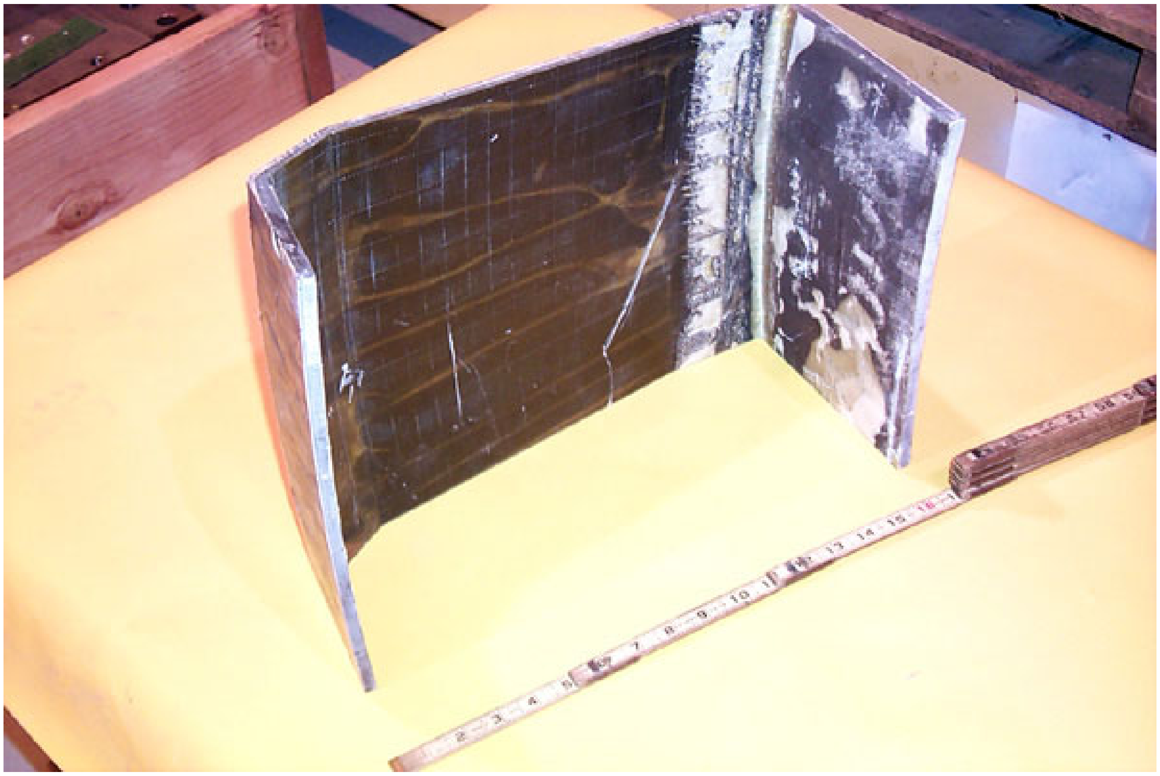

Figure 35 - Large section of ground wrap insulation which easily separated from the coil bundle

Figure 36 - Copper strip separated from the outerwrap and potting compound


Figure 37 - Copper strip separated from the outerwrap and potting compound

3c. TESTING PERFORMED IN THE PPPL MATERIALS TEST LAB

In order to prepare for the in-house mechanical testing of the tension and impact specimens being cut in the machine shop, it was necessary to calibrate the test machines that were going to be used. The selected 'dog bone' tension specimens conforming with the ASTM standards would fit the available grips and load carrying capacity of PPPL's 100-kip MTS servo-hydraulic testing machine (Figure 38). The Charpy impact (notched bar) mechanical tests would be done with PPPL's Tinius-Olson 300 ft-lb testing machine (Figure 39).

Due to the arrival of a new braze furnace in mid-2002, the MTS test machine had to be moved to a new position in the Materials Test Lab (MTL). When this is coupled with the fact that the MTS and Tinius-Olson machines had been dormant for some time, machine re-calibration became essential to the integrity of the mechanical tests. Accordingly, these machines were re-certified to meet the ASTM testing standards. Prior to the start of actual testing, several sample tests were conducted to verify machine performance.

Upon receipt of the final test specimens from the machine shop, each article was carefully measured to certify that it met ASTM's tight geometric tolerances. This process did identify several specimens that did not meet those standards. Whenever possible, those specimens were re-machined and milled so that they could be used in the test program.

Over a period of several weeks, the tension and impact testing of the copper and Nitronic samples was conducted in the MTL. The testing program was successfully completed without complication. A summary discussion of the test program results follows. The complete set of raw and tabulated test data can be found in Appendix A.

The CDA 104 OFHC copper used to fabricate the TFTR TF coils was extruded and drawn to a specification of a minimum 32 ksi yield stress and a minimum 35 ksi ultimate stress. Per the copper standards [Reference 9], these values correspond to slightly less than a half-hard tempered OFHC copper. An overwhelming majority of the copper tension samples corroborated these specifications. The yield stress values from the tests ranged between 32.5-41.7 ksi with a mean value of approximately 34 ksi. The ultimate stresses ranged between 35.9-42.9 ksi with an approximate mean value of 36.4 ksi. Other material properties were consistent with the standards as well. The testing results for elongation ranged between 20-39 percent while reduction of area ranged from 80-86 percent. Figure 40 is a close-up view of the failure surfaces of a typical copper tension specimen that clearly shows the necked down reduction of area. All of these results either met or exceeded the specifications established for the TFTR conductor material.

As was discussed previously, an observation made during the disassembly and machining of the copper was that some of the tension specimens straddled the brazed joints that spliced the long lengths of copper windings together [Reference 10]. The braze process was expected to anneal the surrounding copper, but the brazed joints were intentionally staggered by design to avoid a concentration of annealed copper in the windings. The braze joints themselves were designed to be stronger than the local copper implying that the failures in the relevant tension specimens would be in the copper and not the joints. With one exception, these specimens all failed in the copper. The mean yield stress for this group of specimens was 13.8 ksi and the mean ultimate stress was 30.5 ksi. These values correspond with reference values for copper that is almost fully annealed. Similar consistency with reference values was exhibited for elongations of approximately 50 percent and reduction of areas of over 80 percent. Figure 41 compares two tension samples - one hardened and the other almost fully annealed. The most obvious difference between them is that the ductility in the annealed specimen (with the brazed V-joint clearly visible) grew nearly an inch longer in the tension test prior to failure. The one specimen that did fail in the braze joint showed far less ductility by yielding at 13.8 ksi, but failing at only 26.6 ksi. Elongation was 25 percent, half the annealed values, while the reduction in area was also lower at 76.5 percent.

There were a few intermediary tension test results observed for some of the specimens. They gave test results that fell between half-hard and annealed copper. Although a brazed joint was not physically located in the sample, it was concluded that these specimens were softened by being in the vicinity of a brazed joint and had been affected by heating due to the high thermal conductivity of the copper.

Results for the Charpy V-notch impact tests ranged from 137-156 ft-lbs of energy absorbed for the hardened copper and ranged from 66-119 ft-lbs for the annealed copper. This means that the impact resistance of the hardened copper is greater than that for the annealed copper and should be evident upon viewing the tested samples. Figure 42 shows three Charpy specimens - an untested Charpy specimen, a hardened test sample and an annealed test sample (from left to right). The major difference visible in this figure is that the break in the annealed sample runs much deeper than the hardened sample, indicative of the hardened sample's ability to absorb more impact energy. Figure 43 is a close-up view of the break faces. The annealed sample (on the right) has a larger, cleaner and smoother fracture surface, indicative of lower impact resistance than the hardened specimen, which has a more pronounced hourglass shape and more striated fracture surface.

Every Charpy sample was also used for Rockwell hardness measurements. The hardened copper samples ranged from B30 to B54, which compares favorably to the literature. Rockwell hardness measurements for the annealed copper, however, were more erratic ranging from B19 to B73. The literature also has inconsistent hardness data for annealed copper.

In all of the copper tests performed, the only variable that affected the data was the degree of annealing. The test results did not show any significant deviation as a function of either directionality (in the Charpy samples) or coil origin. TF #8 (the one-hour cut) results overlay closely with results from TF #3 and TF #18 pointing to an excellent consistency in the copper material and the processes used to manufacture the coils.

The Nitronic 33 (Armco 18-3 Mn Stainless Steel, ASTM Grade XM-29, UNS S24000) material test program went smoothly, as well. Reference minimum values for yield and ultimate stresses are 55 ksi and 100 ksi, respectively [Reference 11]. Test results for yield stress ranged from 55.1-62.6 ksi with a mean value of 59 ksi. Ultimate stress ranged from 95.6-104 ksi with a mean value of 101.5 ksi. Note that two specimens failed at less than the specified minimum of 100 ksi ultimate stress, but all specimens exceeded the minimum yield spec. Although the Nitronic tension tests were performed on sets of orthogonal specimens cut from the sidewalls, all results indicate isotropic behavior. Elongation values ranged from 49-62 percent compared with 40 percent minimum in the literature. Reduction of area ranged from 55-59 percent compared with 50 percent minimum in the literature. Figure 44 shows the break faces of a typical failed tension specimen. In the literature, Rockwell hardness values indicate ranges from B96 to a maximum B-scale value of 100. The test samples consistently reached the B100 mark, so measurements were taken on the next level C-scale from C5 to C16.

Charpy V-notch impact results in the literature vary from 232-300+ ft-lbs at room temperature for Nitronic 33. The first few Nitronic Charpy tests conducted at room temperature were consistently greater than 290 ft-lbs. Since the Tinius-Olson impact test machine is a 300 ft-lb device, accurate performance and results could not be assured under these conditions. It was decided to test the majority of the samples at liquid nitrogen (77K). The literature indicates a minimum 30 ft-lb impact strength for Nitronic 33 at 77K. Test results ranged from 34-51 ft-lbs, exceeding the established minimum for impact strength. These results can be extrapolated and coupled with the few tests performed at room temperature resulting in a conclusion that all Charpy specimens met the minimum established impact resistance requirements. Charpy tests results were isotropic. Figure 45 compares Charpy specimens at room temperature (left) and LN2 (right). Lower temperature makes the metal more brittle, thereby reducing its impact resistance. Due to its ductility, the room temperature sample readily absorbed 300 ft-lbs of energy, while the LN2 sample broke at approximately 40 ft-lbs. Figure 46 compares the fracture faces of these two samples. The room temperature sample (left) has a rough, striated face indicative of high impact resistance. The LN2 sample (right) has a smooth, clean fracture surface with slight shear lips at the edges, which is normal.

The Nitronic 33 material yielded very consistent test results that, with very few exceptions, exceeded the minimum program specifications. All measured properties were isotropic and uniform from coil case to coil case. As with the copper, nothing in the test results distinguished the TF #8 samples from the TF #3 and 18 samples. This virtually assures that the anomalous TF #8 cut was due to the cutting procedure itself rather than the materials.

Figure 38 - 100-Kip MTS Servo-Hydraulic Test Machine

Figure 39 - Tinius-Olson 300 Foot-Pound Impact Machine


Figure 40 - Typical Failure Surface of Copper Tensile Specimen

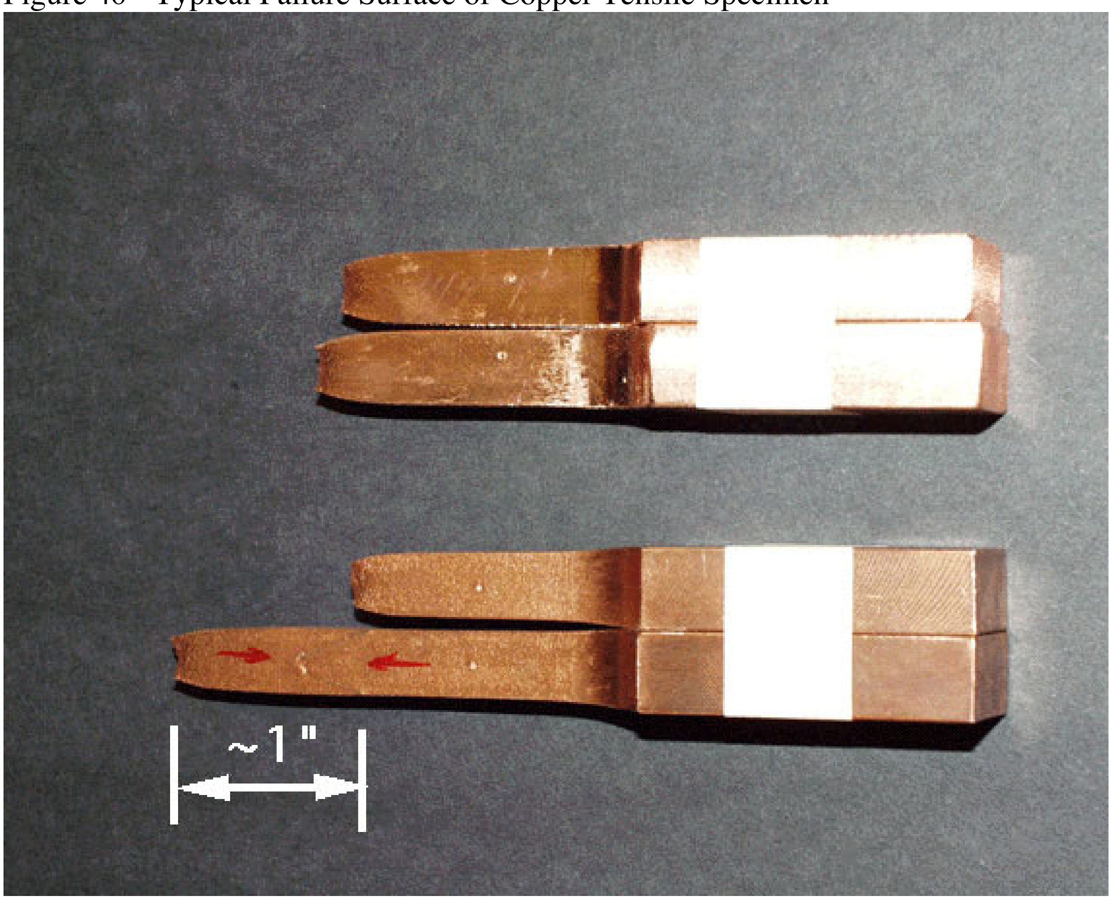

Figure 41 - Comparison of Hardened vs. Annealed Copper Tension Specimens

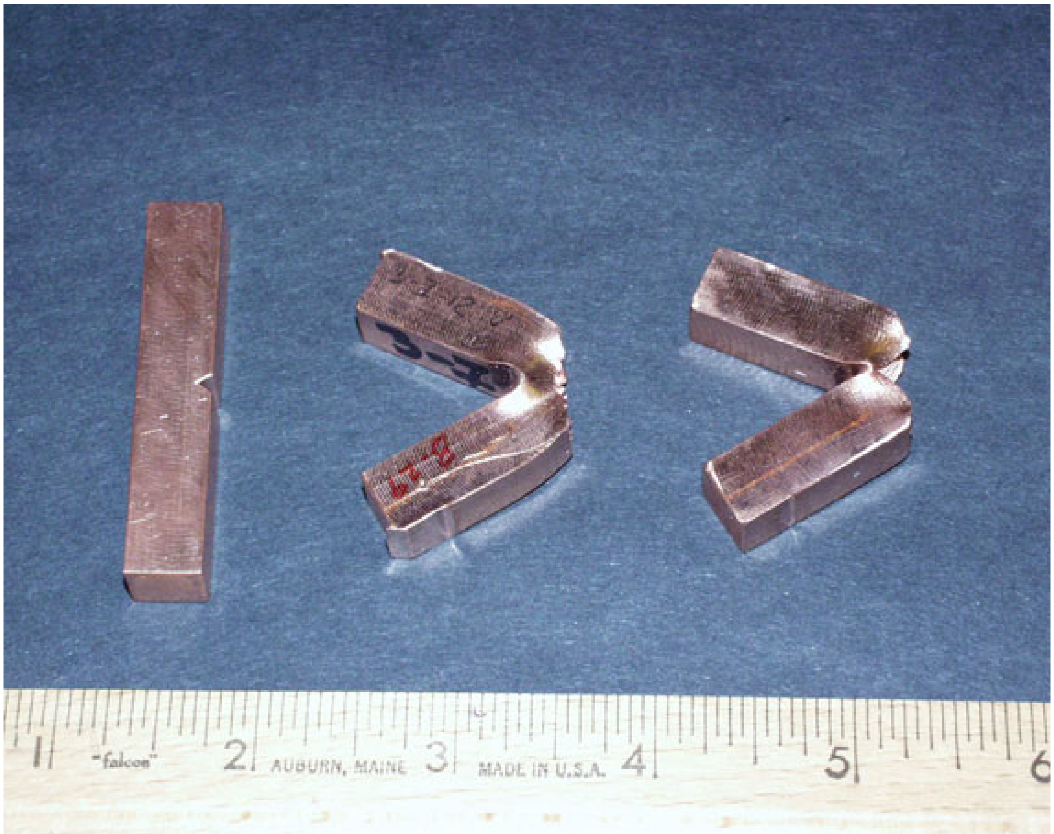

Figure 42 - Copper Charpy Specimens - Untested, Hardened, Annealed (from left)

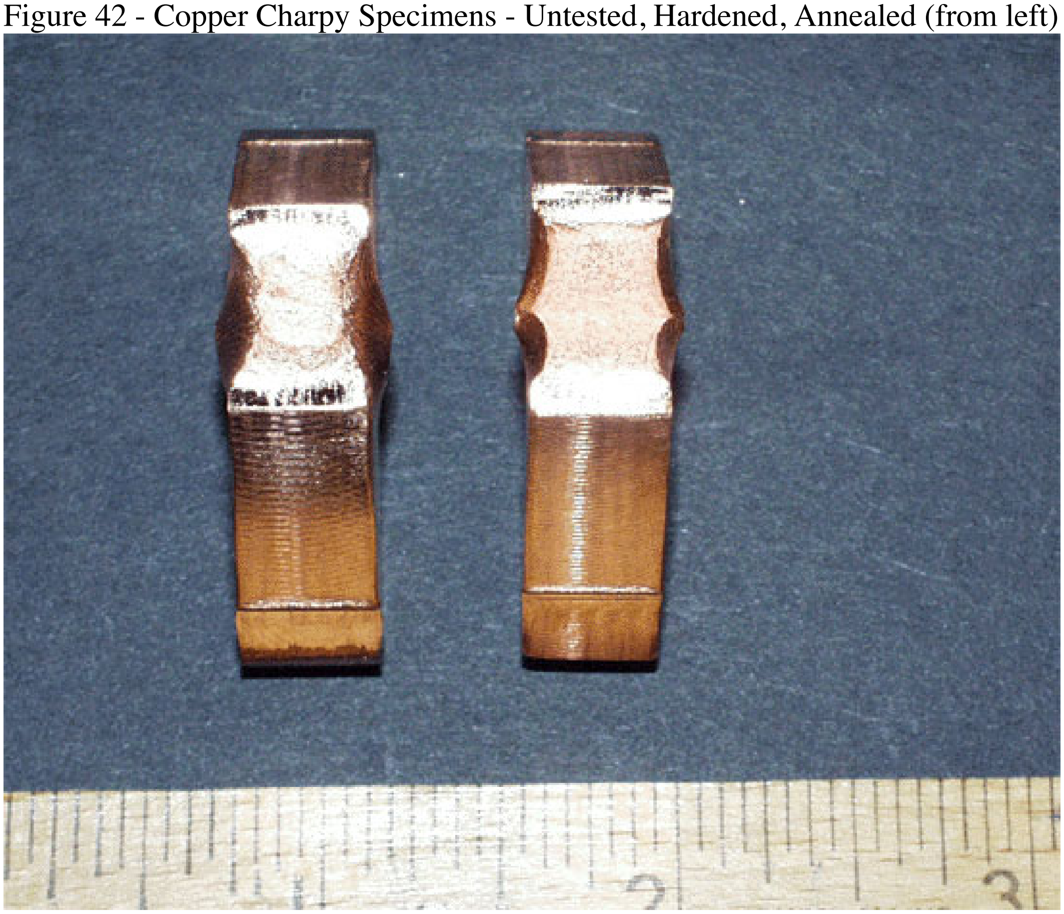

Figure 43 - Copper Charpy Impact Fracture Faces - Hardened (left) vs. Annealed

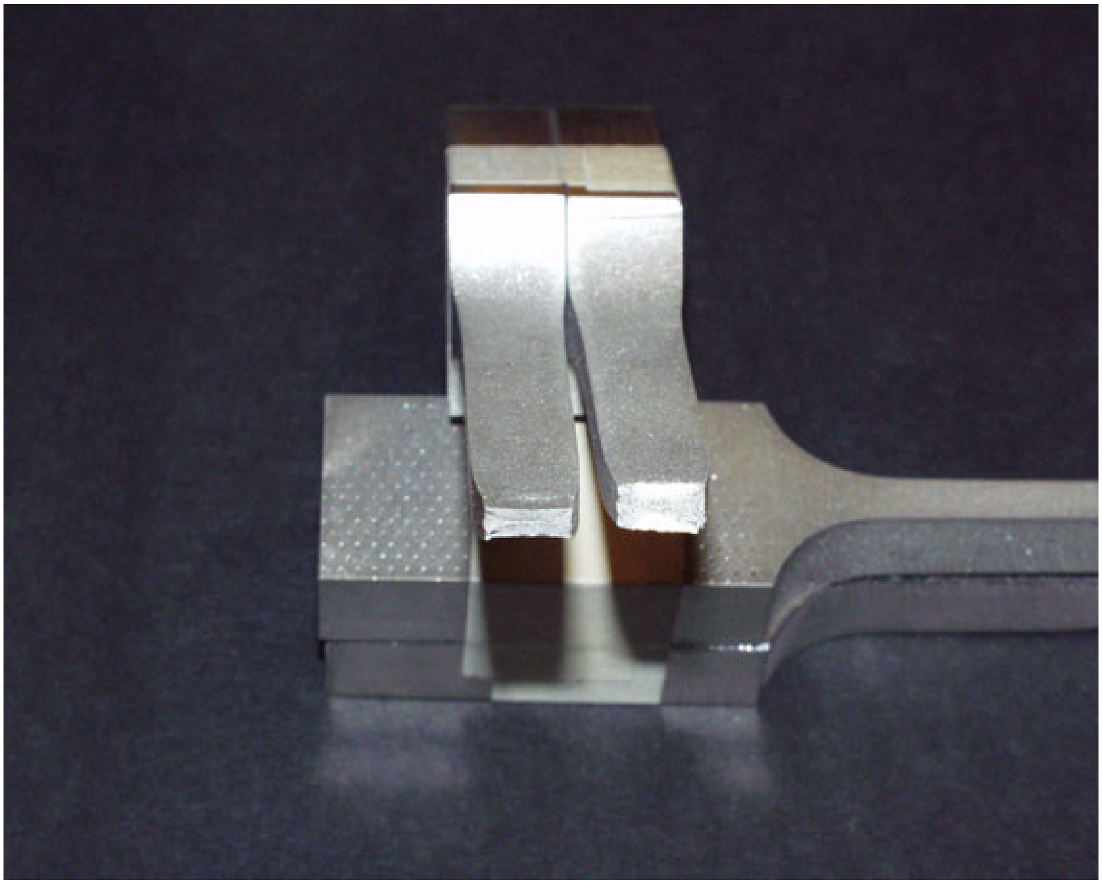

Figure 44 - Typical Failure Surface of Nitronic 33 Tensile Specimen

Figure 45 - Nitronic Charpy Impact Test Speciems - Room Temperature (left) vs. LN2

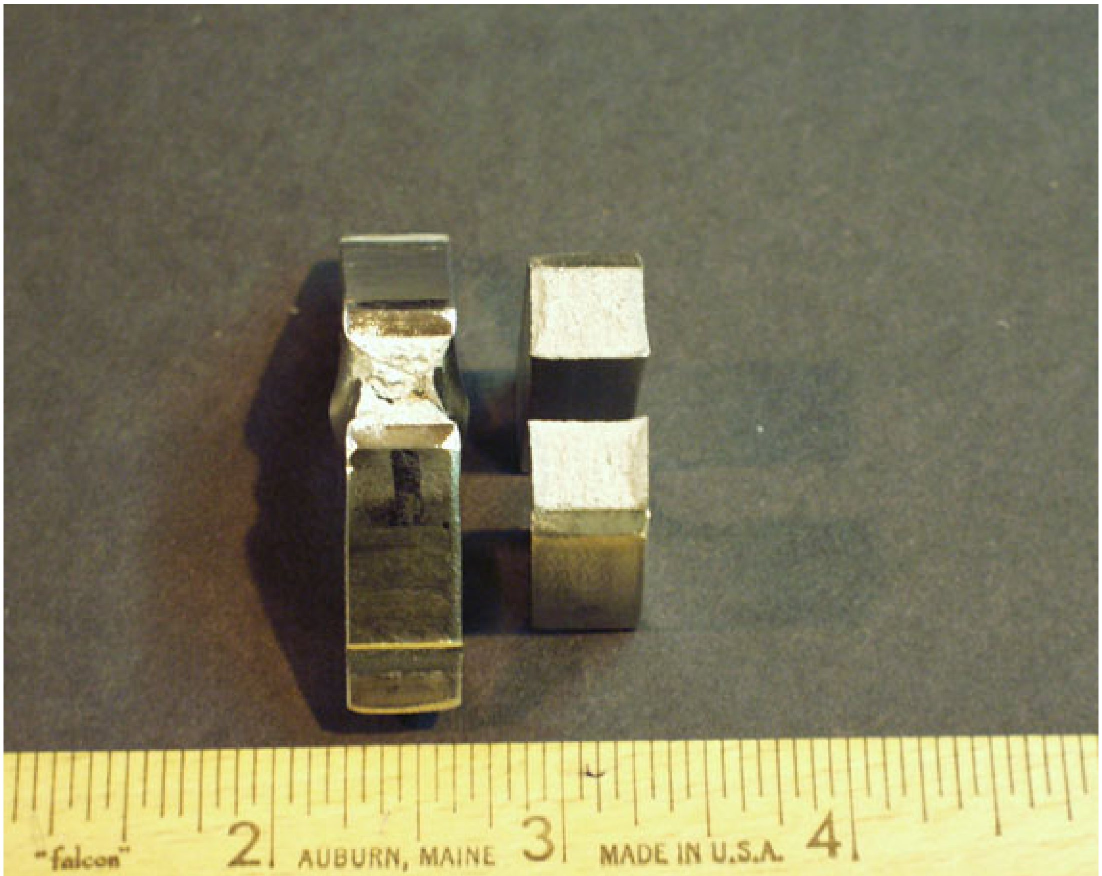

Figure 46 - Nitronic 33 Charpy Impact Fracture Faces - R.T. (left) vs. LN2

3d. TESTING PERFORMED OUTSIDE OF PPPL

During TFTR operations, when TF coil coolant leaks were observed at the water fittings, numerous attempts were made to locate, explain and repair those leaks. Among the techniques employed were borescoping, flushing with solvents and resealing with various compounds. Nevertheless, some of these leaks could not be resolved or repaired adequately resulting in the use of Fluorinert as the conductor coolant. The ability to perform actual metallurgical analyses on these leaking fittings was obviously limited during TFTR operations to in-situ, non-destructive testing.

Two metallurgical evaluations [References 12 & 13] were performed on water fittings and copper specimen samples available from sources like one of the spare TF coils (e.g., the 250 coil). Since the required technology to do this work was unavailable at PPPL, outside contractors were used. These tests were conducted for the purpose of doing metallograpic and micrographic analyses of grain sizes and any defects in the samples. This information would then be utilized in an evaluation, including failure analysis, of the specimens. One particular mode of copper deterioration that would contribute to possible cracking and leaking in the fittings is hydrogen embrittlement. Ordinarily, using oxygen free copper, such as the OFHC CDA 104 used for the TFTR TF coil bodies, is sufficient to avoid hydrogen embrittlement. But in 1992, one vendor [Reference 12] reported finding evidence that it did, indeed, exist in the test samples provided and that the copper oxidation leading to embrittlement may have inadvertently occurred somehow during the fabrication process. It was also noted that with hydrogen embrittlement, defect growth is a progressive condition, meaning that once oxidized copper is present, the embrittlement could continue gradually with time. Higher temperatures would likely accelerate embrittlement. Ultimately, a microscopic defect will manifest itself as a crack leading to a potential leak.

The other metallurgical evaluation performed in 1995 [Reference 13], however, found no evidence of hydrogen embrittlement or abnormal grain growth in the water fitting samples it received and tested.

With the TF #3 water fitting section set aside as part of the D&D project (Figures 19, 21, 22), actual leaking fittings could finally be extracted and subjected to a rigorous metallurgical evaluation and analysis. To be consistent, both vendors that conducted the prior work were contacted about regarding the opportunity to do the follow-up work on the TF #3 fittings. Unfortunately, one vendor (Structure Probe) declined due to their policy of not handling activated materials. The other vendor (City Testing and Research Laboratories) was prepared to examine these fittings.

There are fourteen water fittings on each TF coil numbered 1 through 7 then 10 through 16. Figure 47 is a schematic that shows the locations of these fittings. It was decided that the vendor would do a metallurgical examination on three selected fittings – numbers 3, 13 and 14 from TF #3. Prior to this metallurgical work, these three fittings had the following history:

- Water fitting 3 had an unresolved leak. No defect had been found.
- Water fitting 13 was known to have cracks in the vicinity of the brazed joint connecting the water fitting outer tube to the main body of the coil (Figures 48 & 49). Attempts had been made to patch these cracks in-situ, but that effort was never completely successful.
- Water fitting 14 was never known to have a leak and was to serve as a reference for the metallurgical tests.

In the RESA building machine shop, the TF #3 water fitting coil section was carefully dismantled and cut to preserve the water fittings for these tests. A typical extracted water fitting cut from TF #3 is shown in Figure 50. As planned, fittings 3, 13 and 14 were sent to the City Testing and Research Laboratory for evaluation. The primary questions asked over the years which had to be answered were whether any hydrogen embrittlement had occurred in these fittings which might have caused the known cracking and to identify the material composition of the brazed outer water fitting tube. During TF coil construction, the coil windings themselves were clearly specified as OFHC copper, but the copper alloy for outer fitting tubes had not been formally designated. If, in fact, these tubes were made from an oxygen bearing copper alloy, that would have been the likely source of hydrogen embrittlement, if any was found.

City Testing and Research Laboratories completed its metallurgical evaluation of the submitted fittings. Each fitting was examined in several key locations. Their findings are documented in Appendix B [Reference 14]. The principal findings and conclusions in Reference 14 are as follows:

- The outer water fitting tubes are made of OFHC copper.
- No hydrogen embrittlement was found in any of the water fitting samples tested.
- "There is no evidence of any unusual microstructural indication or any abnormal grain growth" in any of the samples.
- Cracks and their resulting leaks in fitting 13 are not related to the brazed joints.
- The cracks in fitting 13 "appear to have been caused by a thin wall during manufacture of the assembly (i.e., cavity not centered between section walls)". There is no evidence of fatigue or crack propagation. The cracks are indicative of a non-ductile type failure.
- Fittings 3 and 14 did not show any evidence of cracking. The reported leak at fitting 3 does not appear to originate in the fitting area.

It was upon the return of these cut-up tested water fittings that the probable cause of many of TFTR's water fitting leaks became apparent. Figure 51 is a view of the fitting 13 crosswise cooling channel linking the external water fitting to the extruded cooling channel in the body of the winding. Not only is this crosswise channel severely deformed, but the channel itself is not centered within the thickness of the turn, leaving a very thin wall of copper. In this case, the deformation in the cooling channel has resulted in a thru-crack in the turn. This deformation was almost certainly caused during the manufacturing process. The sequence of brazing the fitting in the copper plate probably annealed the local copper in the crosswise channel. As one moves away from the braze area, the copper transitions back to hard (32 ksi yield) copper. The copper plate is then wound into the coil turn, and buckling in the annealed crosswise channel can easily occur as the metal acts like a hinge.

The other two tested fittings also had this same buckled phenomenon, however, the crosswise cooling channel was centered better in those turns, avoiding a thin-walled thru-crack. It is not hard to imagine that out of the 280 water fittings on the TFTR TF coils, several others may have had leaks where the annealed copper crosswise channel was not properly centered in the turn.

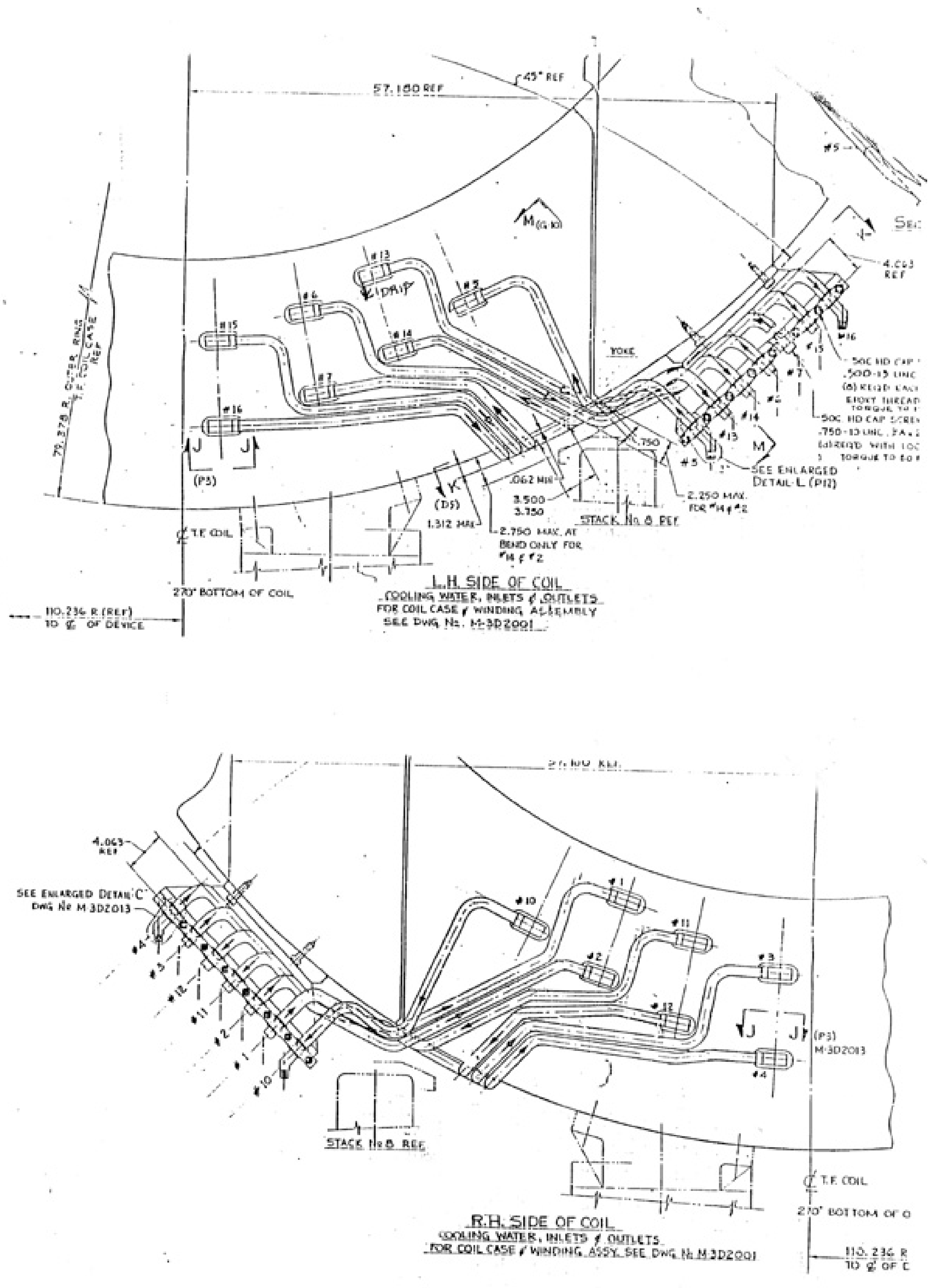

Figure 47 - Schematic of the Locations and Numbering of TF Coil Water Fittings

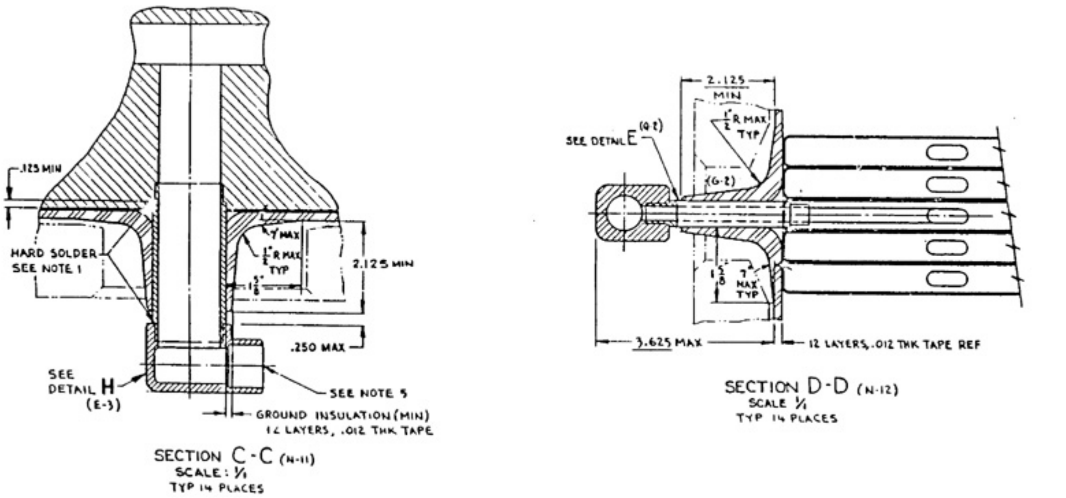

Figure 48 - Typical TF Coil Water Fitting Detail

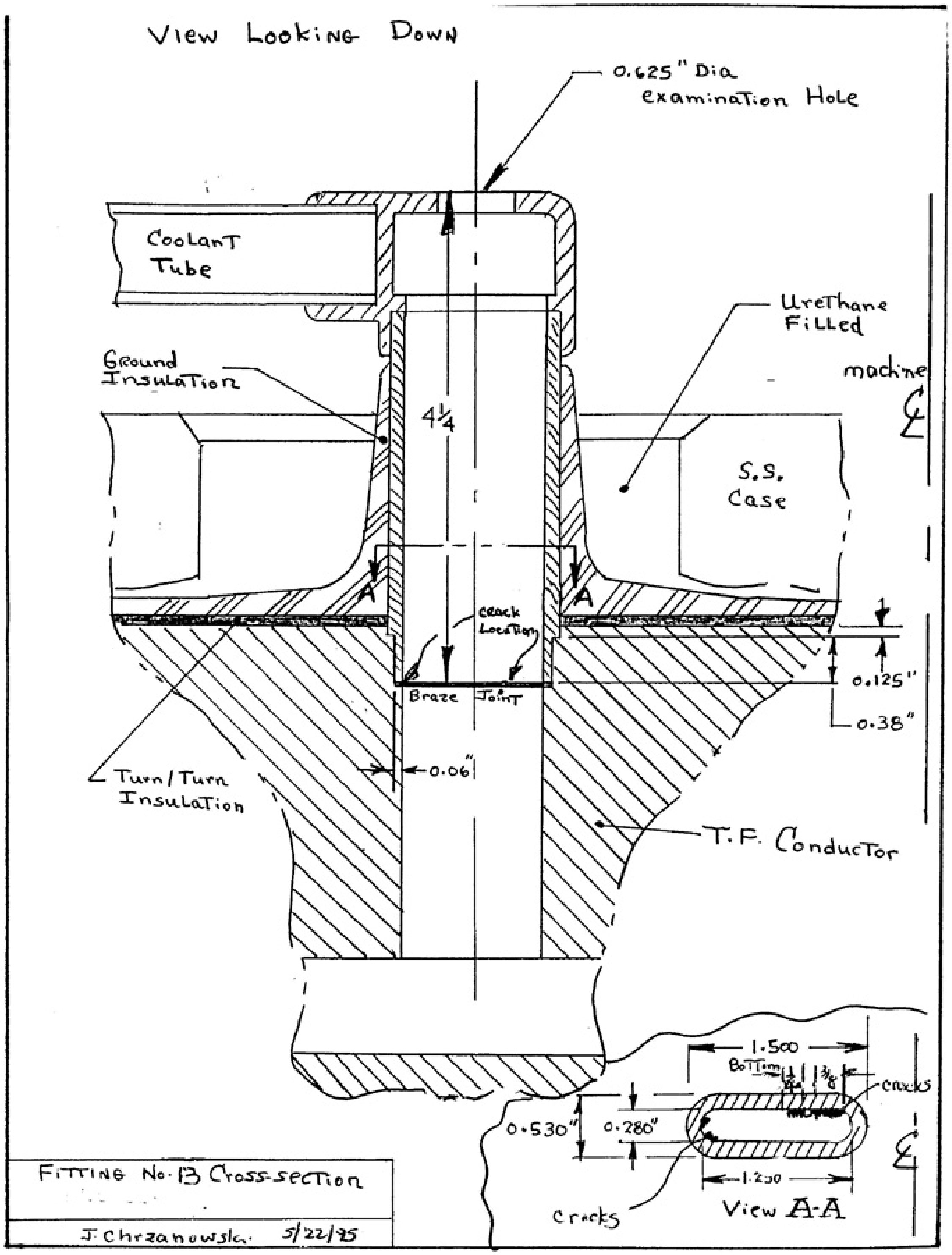

Figure 49 - Schematic Detailing TF #3 Water Fitting Crack Observations

Figure 50 - Extracted Water Fitting Section From TF #3 For Metallurgical Examination

Figure 51 - TF #3 - Fitting 13 - Deformed Crosswise Cooling Channel

4. SUMMARY AND CONCLUSIONS

As part of the TFTR D&D project, an extensive examination and test program has been conducted on the TF coils while the machine was being dismantled. Coils were subjected to visual, photographic, physical, mechanical and metallurgical inspection and testing.

Visual and photographic inspection has confirmed the consistently good quality in the manufacture and performance of the twenty TF coils. Initially, no defects, other than very minor geometric anomalies, could be found in the coil sections as they were cut in the TFTR Test Cell. Once the selected coil sections from TF #3 and 18 were completely disassembled, a few defects emerged that indicated an inconsistent and less than perfect bonding of the copper windings to each other. However, these occasional lapses did not appear to significantly affect the integrity of these complex assemblies.

Mechanical testing revealed that the material properties of the OFHC copper and the Nitronic 33 stainless steel case met or exceeded the original design specifications in virtually every sample tested. Tensile yield and ultimate stresses, as well as other properties, generally fell into a narrow range and showed no signs of deterioration as a result of either repeated cyclic mechanical and thermal loads or activation incurred during TFTR operations. Local annealing of the copper windings in the vicinity of spliced braze joints were expected and examined as well. The pattern of measured copper strengths showed no sign of hard copper softening or soft copper hardening, which, if it occurred, would be indicative of turn-to-turn slipping and redistribution of load. Although the turn-to-turn bonding of the copper windings were found to vary, enough bearing and friction load was present during operations to negate these irregularities, prevent any measurable slip, and result in the coils performing at design levels.

One coil, TF #8, which cut with greater ease than the other nineteen coils in the TFTR Test Cell was also subjected to comprehensive testing, but the results and observations were consistent with TF #3 and 18.

Three water fittings from TF #3 were sent to a vendor for metallurgical testing. Two of these fittings had a history of leaking. Although hydrogen embrittlement was suspected as the cause of these leaks, the results indicated that none had occurred. When these fittings were completely cut-up and examined, it was evident that the crosswise cooling channels had routinely buckled and deformed as part of the original manufacturing process. If a channel was not centered in the turn thickness, the resulting thinner wall would form thru-cracks due to the local annealing of the copper in the braze area and the forces of winding the coils.

A leak suspected at the lead spur of TF #18 could not be resolved through borescope inspection but can still be examined in more detail at some point in the future. Other less critical but important tests that can be considered for future evaluation are the testing of the Inconel case bolts and shear testing of the turn-to-turn copper epoxy bond strength which appears to have a broad span based on the work done to date. In order to accommodate the possibility that there may be an opportunity for follow-up testing, a variety of TF coil samples, including the TF #18 spur region, have been stored in the Rad Waste building.

TFTR's success can be attributed, in large part, to the well designed and constructed TF coils, whose overall quality has been confirmed by this test program.

5. ACKNOWLEDGEMENTS

This work was supported by the US DOE under Contract No. DE-AC02-76-CH03073.

A project of this scope and magnitude could never have been completed without the cooperation and dedicated efforts of many individuals. The author would like to express special thanks to the following people whose support was essential to the successful completion of this work: Mike Williams, Erik Perry, Jim Chrzanowski, Mike Viola and Steve Kemp for their guidance and administrative assistance; Keith Rule in the Rad Waste Building; Bob Hitchner from Health Physics; Bill Zimmer and Bob Clark in the Machine Shop; and grateful appreciation to Steve Jurczynski in the Materials Test Lab for his countless hours of effort performing the actual mechanical tests and data reduction.

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