TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 32

Coil Assembly Documentation

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MASTER

COIL ASSEMBLY DOCUMENTATION
for the
TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

PRELIMINARY DESIGN REVIEW

SDRL 32

13-950727-BW-HBELL-01

Prepared for the University of California
Lawrence Livermore National Laboratory
Subcontract B235308

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1. INTRODUCTION

This document is intended to address the contract requirement for providing coil assembly documentation, as required in the applicable Technical Statement of Work:

TSOW §1.3.10:... "Provide preliminary procedures and preliminary design and – supporting analysis of the equipment, fixtures, and hardware required to integrate and align the impregnated coil assemblies with the coil cases and intercoil structure."

Each of the three major processes associated with the coil case and intercoil structure (ICS), TF Case Fabrication, Coil Preparation for Case Assembly, and TF Octant Assembly, are examined in detail. The specific requirements, processes, equipment, and technical concerns for each of these assembly processes is presented.

The documentation presented begins with the receipt of the impregnated coil (Ref. SDRL-22 for the specifics regarding manufacturing of the impregnated coil). The coil at this point has the ground plane insulation and the electrostatic shield installed and impregnated with epoxy resin. This document covers the scope of work occurring prior to delivery of the TF Magnets to the test cell at Princeton. The appendix of this document contains a copy of the TF Case Assembly Procedure. Not included in this document is the final piping, wiring, and alignment of the octants in the test cell. The piping, wiring, and alignment work not included involves primarily the installation of helium isolators on the coils' helium stubs and the associated helium piping, the helium supply to the splices and the associated isolators, splice support structure, and the routing of coil instrumentation leads. The final adjustments to the octant alignment will be performed after the mapping of the magnetic field in the test cell at PPPL. The work to be done in the test cell at Princeton will be presented as part of the Installation Plan and Procedures (Ref. *TSOW §3.2.10.2* to be performed during Phase II of the contract).

The processes included in this document are preliminary in nature. As the TF design evolves and delivery requirements are further defined, the processes will be modified to accommodate them.

2. TF CASE FABRICATION

The fabrication of the TF case will be handled through subcontract to Babcock & Wilcox, Nuclear Equipment Division (NED), Mt. Vernon Works. Their extensive experience in fabricating and machining large stainless steel reactor vessel and steam generator uniquely qualifies them to fabricate the TF cases. The manufacturing engineering staff at B&W NED works closely with B&W, Accelerator and Magnet Systems personnel to develop processes which meet design requirements, minimize risk, and satisfy cost goals.

2.1 REQUIREMENTS

The TF Case is the primary structure assuring proper alignment of the coils within the case and with other octant cases. This alignment must be maintained despite wide temperature swings, high stresses, and radiation.

2.2 PROCESSES

The TF case manufacturing processes are detailed, but still somewhat conceptual at this early stage of the program. Figure 1 below shows a simplified process flow diagram of the case manufacturing process. A more detailed process outline is presented in Appendix I containing a preliminary process breakdown of the fabrication operational sequence for the TF case including conceptual sketches of fixturing and fabrication. While *TSOW §1.3.10* does not mention fabrication of the case as part of this SDRL, the case fabrication is so critical to the final coil alignment that to ignore its fabrication would be remiss and the sharing of such information is critical to the success of the program.

2.3 TOOLING & EQUIPMENT

Tooling and equipment play a fundamental and vital role in determining the success or failure of any process. The process capability of any tooling equipment is closely tied to the component being processed. Establishing the capability of a given machine or fixture to achieve close tolerance work for a particular part profile can only be achieved by a process qualification. The welding development program, 1/4 scale mock-up, and prototype in Phase II of the TPX program will serve that function. The similarities between the TF case structure and the large vessels fabricated in B&W NED Mt. Vernon in terms of materials, weld joint configurations, tolerances, and processes provide an experiential base, which will shorten the TF case fabrication development effort. These similarities also provide evidence of significant relevant capabilities in terms of process development.

2.3.1 Key Equipment

The fabrication of the TF Case will require some significant equipment, heavy lifting capabilities (ref. Figure 2) and floor space. The major equipment is listed in detail below. As to floor space, the B&W facility at Mt. Vernon has adequate floor space available in the facility. This floor space will become critical to supporting the fabrication of multiple octants in parallel. The floor space also becomes an issue since final coil cover machining can only proceed after the last octant is completed. The trial fit up of the octants will also require a significant amount of floor space.

2.3.1.1 Plate Rollers and Benders

Plate rollers are required to produce the myriad contours in the structural plates of the TF case assembly. Both the coil cases and the ICS have a number of bends which can only be cost-effectively manufactured by plate rollers and benders. B&W currently has plate rollers and benders with adequate capacity to handle all the structural components of the TF cases. They are capable of handling stainless steel plates up to 25 cm thick and 4 m wide.

2.3.1.2 Welding Equipment

The TF Case fabrication welding must be performed on a large weld positioner to achieve the proper down-hand weld head position. The weld head position is critical to achieving uniform welds throughout the case assembly to minimize welding stress differentials, distortion, and cracking. The welding tooling, included in the conceptual sketches found in Appendix I, will provide the proper control of the case assembly constituents during the TF welding assembly. B&W currently has weld positioners with up to 250 ton capacity.

2.3.1.3 Boring Mill / Machining Center

To hold the tight tolerances a very large boring mill or machining center is required. The envelope on this machine must be at least 15' (X) by 15' (Y) by 10' (Z) and it should be equipped with a rotary table. While smaller machines without rotary tables could be used, the resulting stack-up of tolerance due to set-up error would make achieving the required precision virtually impossible. The machine should also have on-machine gauging to cut down on the number of set-ups required. Elimination of the additional set-ups on the mill, when inspection indicates machining is required to correct an out of tolerance equipment, is cost effective and improves product quality by reducing the sources of case variability

Figure 3. Large Boring Mills Similar to Those at B&W NED Mt. Vernon Works

Fortunately, the B&W Mt. Vernon facility has a number of horizontal boring mills and machining center with the capacity to handle the TF case. This means that machine downtime will not affect the machining of the octants since the work can be shifted to an equally capable machine should a machine develop problems. In fact, the bed of the Farrell Mill is large enough to do the final trial assembly of all the TF octants together. This is critical to achieving the final coil cover machining tolerances to assure proper coil alignment.

2.3.1.4 Annealing Furnace

The TF case will be subjected to an annealing cycle to reduce the internal stresses present in the case after the assembly welding. The gas furnaces in the MT. Vernon Works (ref. Figure 4) are easily capable of handling the TF cases both in terms of size and thermal regimen control.

Figure 4. Large Heat Treatment Furnace for TF Case

2.3.2 Key Tooling

The case fabrication process will require the fixturing detailed in Appendix I. There are basically two groups of tooling needed for building the TF cases. The first group of tooling is the assembly welding tooling. The second group of tooling fixtures is related to the machining of the subassemblies of the octant and the octant. These two groups of tooling are consistent with each other to assure they function successfully in concert to achieve the demanding tolerances.

The first group of fixtures include the coil case assembly welding fixturing, the ICS welding fixturing, and the final case welding fixturing. The conceptual designs included in Appendix I are preliminary and will evolve as the development effort proceeds.

2.4 TECHNICAL CONCERNS

Two major concerns emerge in examining TF coil case fabrication. The first and most significant is controlling case distortion. The second is achieving the requisite precision in machining the case nose region and coil locator pads. The attachment of fiducials early in the case fabrication process provides a constant and common reference for all the subsequent processing. These concerns, while significant, are manageable with the mitigation plans in place to deal with them.

2.4.1 Case Distortion

The most significant concern in the fabrication of TF coil cases is distortion of the case. Distortion can be imparted due to welding, machining, and even shipping. The processes shown in Figure 1 were specifically tailored to minimizing case distortion. Specifically, the case receives an anneal to relieve stresses after fabrication welding of the entire structure with the obvious exception of the coil cover and chimney box welding. The coil cavity is machined after the anneal but this is a coil free-path verification with no metal removal anticipated. The only material removed during this machining in the coil cavity will be from the G-10 coil locator pads. These pads will be machined to achieve the critical dimensions required for coil location within the case. This pad machining will not impart stresses to the case.

Distortion of the case during fabrication is a major concern. During the early stages of Phase II of the TPX contract, an extensive welding development program will be performed to develop welding parameters, produce the parameters required to predict welding distortion and stresses, and prepare for the production of a 1/4 scale mock-up of the TF case. This 1/4 scale mock-up will verify and help difinitize welding sequences and parameters. Early in the fabrication process, fiducial sockets are attached to the case. These fiducials allow the constant monitoring of the case features relative to those fiducials. This common set of reference points eliminate the tolerance accumulation, which would cause a systematic error, preventing the coil cavities from achieving the required tolerances.

Reducing the stresses in the case through an annealing process, will reduce the likelihood of subsequent operations and shipping vibrations causing stress relief resulting in case distortion. The 1/4 scale case mock-up may be employed as a test piece for transportation vibration induced stress relief. Additional steps such as air-ride trailers will be used to reduced transportation vibration.

2.4.2 Tight Machining Tolerances

The tight machining tolerances inherent in the TF case design are directly related to the coil position requirements. The coil position is critical to minimizing the field errors associated with the TF structure. To minimize the amount of precision machining, the coil cavity only has one surface that is precision machined, the G-10 locator pads. These pads are G-10 blocks bonded onto the coil contact regions. The use of these pads precludes the need to machine the entire coil cavity to achieve an acceptable case to coil positional tolerance. The TF octant case will be machined using a single massive fixture, which uses the fiducial locations as base reference points. This same fixture is used during nose region machining to achieve the tight requirements. To

ensure the octant to octant interface is machined to the same precise levels, the same fixture will be used for final case cover machining. The machining centers being used for these operations are equipped with rotary tables, allowing them to machine the two coil cavities and nose region in a single set-up, eliminating variability due to set-up.

As part of Phase II of the TPX program, B&W will utilize the 1/4 scale mock-up to evaluate precision machining processes. Any changes required will be employed in the prototype coil case and subsequent octant processing.

3. COIL PREPARATION FOR CASE ASSEMBLY

The coil preparation for case assembly occurs after the last Vacuum Pressure Impregnation (VPI) operation, but prior to insertion of the coil into the TF case. The last VPI operation provides protection for the electrostatic shield and provides a uniform surface for installing case interface

components (locator pads). Coil preparation for case assembly is critical to positioning the coil in the coil cavity of the TF Case accurately, as this operation provides the final physical reference between the coil and the case. The success of this process is as dependent on inspection methods, as it is on manufacturing methods. For this reason, the development efforts in Phase II will address the combination of variability due to inspection methodology and variability due to manufacturing methodology.

3.1 REQUIREMENTS

The coil preparation process requirements are largely a function of achieving the tolerances depicted in Figure 5. Once two coils and a case have been fabricated, Design Engineering will provide the ideal location for those coils within that specific case, relative to the TF case fiducials using an analytical engineering model. To thoroughly understand the stringent nature of this requirement, mentally construct an envelope of the same outside dimensions as the as-built coil, but larger by 0.005". Now place this envelope so that it is in the perfect theoretical position relative to the X, Y, and Z axes and the angles of rotation about those axes. The coils after preparation and installation must be within that envelope. Given there are six degrees of freedom of coil movement (X,Y,Z axes and the rotation about those axes) contributing to coil misalignment, the positional requirements are extremely tight. Fortunately, coil placement error in the X and Y axis can be countered somewhat by optimizing the placement of coils within subsequent octant cases, adjusting case to case alignment, and selective assembly of octants. The single most stringent requirement is the ± 0.005 " tolerance about the 22.5° angle formed between the best fit planes of the two coils within an octant. No mitigation exists for violating this dimension.

3.2 PROCESSES

The coil preparation process for assembly is a conceptually simple but extremely exacting in execution. The process diagram (ref. Figure 6) shows the process steps in an overview form. For a more detailed process description, please refer to Appendix II. The key processes are the QC survey techniques (Eddy Current Inspection and Laser Survey) and the G-10 machining / handworking processes. The detailed functional descriptions of the QC equipment and techniques are included Sections 3.3.2 and 3.3.3.

During all QC inspections, the coil is supported on the coil preparation station's support stands exactly the same way as it is in the TF octant case. This consistency is absolutely necessary because otherwise, correlation between dimensional data taken before insertion and that taken after insertion would be problematic. This difficulty is due to a minor tendency of the coil to sag between support points.

The G-10 coil locator pads exist as blanks initially. The contact (radius) surface of the locator pad which contact the case's locator pads are already machined (ref. Figure 5). When the analytical model generates the individual locator pad thicknesses, the coil locator pad surface which is to be attached to the coil is machined to achieve the desired pad thickness. This surface serves as the glueing surface for attachment to the coil.

The coil is lifted and the pads attached. Process development will be performed to establish the process capability of this operation. The coil is lowered back to the support stands for an inspection using the laser tracker and the temporary fiducials. Given the loads the G-10 will be under, there will be some compression and deformation of the pad. The amount of deformation will be quantified during process qualifications. After the survey, the coil is lifted and the pads handworked with extremely fine abrasive pads to achieve final pad height. The pads on the coil inside diameter are modified in a similar fashion. The coil is transported to the case assembly stand for insertion and the survey, adjust, and survey cycle repeated until final coil position is achieved.

3.3 TOOLING & EQUIPMENT

Tooling and equipment for the coil preparation will be specialized for the most part. The only piece of multipurpose tooling listed in this section is the laser tracker system. The coil preparation stands, the eddy current system, and the coil lifting fixture are all optimized for coil manufacturing. The coil lifting fixture description is included in Section 4.3.2 as the insertion portion of its functions is the more critical. Strong emphasis in developing the conceptual designs for the tooling was placed on simplicity and functionality. Complexity was added only in situations where product quality and manufacturability were improved (laser tracker system)

3.3.1 Coil Preparation Station

The coil preparation station consists of eight adjustable pedestals, which are located coincident with the pads on the coil. The height of the individual pedestals can be adjusted to mimic the locator pads in the coil case. The individual support pedestal allow the coil preparation to occur with the coil supported in the same way it is in the coil case during its inspection. This system interacts with the eddy current system, the laser tracking system, and the coil lifting/insertion fixture.

3.3.2 Eddy Current System

The eddy current system provides a means for identifying the location of the conduit within

the impregnated coil. This inspection technique is capable of penetrating the electrostatic shield, the ground wrap, and the impregnated fiberglass. The depth of insulation over each turn on the surface of the winding can be determined. The position of the conduit will be mapped on all four sides of the coil at numerous points around the coil. The physical dimensions of the coil are also measured at these points to provide a reference dimension. These positions and dimensions are related back to temporary fiducials mounted on the coil using the laser tracking system (see Figure 7). A plane of best fit is then constructed from the data to estimate the magnetic centerline of the coil (ref. Figure 8). Then, this centerline data is inserted into an engineering model of as-built TF octants and coils to optimize the coil position relative to other coils within the TF magnet system. Finally, the model is used to generate the final locator pad heights required to achieve the optimum coil position.

The measurement error associated with this approach will be determined as part of the qualification program. Samples will be fabricated in Phase II of the program, measured with the system to determine gauge repeatability and reproducibility, and then destructively evaluated. The results of that destructive evaluation will be compared to the eddy current data to clearly define system the measurement system's performance.

3.3.3 Laser Tracker System

The laser tracking system provides a consistent reference for coil preparation. Because of its iterative nature, the coil preparation procedure is a perfect application for a laser tracker. Initially, it is used to survey the windings but its role is much broader than that. Once the final coil locator pad height has been produced by the design engineering model, the coil is lifted, the pads are aligned, and the pads are glued to the coil at the proper locations. The coil is then lowered back onto the pedestal for pre-insertion survey. The tracking system is then activated to check the coil fiducials to ascertain whether the proper coil alignment has been achieved. Following any minor handwork to the locator pads to achieve the proper coil position, the coil is ready for insertion into the waiting case. The laser tracking system also provides as-built data on the case

the case operation as well. The coil is checked in the case using the laser system to assure the final desired position of the coil is achieved. The laser system will also prove invaluable during octant assembly trials at the Mt. Vernon facility in preparation for final machining of the case interface surfaces. The tracking system will also be available for installation of the octants into the Test Cell at PPPL.

The relatively high cost of this laser tracking system is offset by the tremendous reductions it allows in set-up of inspection and assembly operations, and its accuracy. Similar systems are used in the fabrication of other high precision large assemblies in a number of other industries, such as the aerospace industry (Boeing, among others).

3.4 TECHNICAL CONCERNS

The current field error allocation for TF magnet system severely restricts the placement of the magnets within the case. Measurement error will consume at least 40% of the total allowable positional error associated with each coil. The error associated with eddy current measurement has been identified as $\pm 0.001''$. The laser tracker system will be hard pressed to attain accuracy of

$\pm 0.001''$ for a part of this size. Consequently, $0.004''$ of the total allocation of $0.010''$ has been consumed. Add to that the error associated with the distribution of the conductor within the winding not being perfectly distributed. This conductor placement error could cause some shift in the field from the calculated values for the field position.

The combination of these three sources of error rob assembly of all but a fraction of the total misalignment tolerance. Positioning a non-rigid structure of these coils' size resting on G-10 pads to within $\pm 0.002''$ is extremely difficult. Fortunately, by reviewing the as built data, the coil positions can be manipulated to compensate somewhat for these errors. Increasing the TF field error allocation would significantly reduce the labor costs for manufacturing the coils and inserting the coil into the case. A total positional tolerance of $\pm 0.050''$ would allow tooling controls to be implemented that would reduce both the inspection costs and the manufacturing labor content.

4. TF OCTANT ASSEMBLY PROCESS

The octant assembly of the TF coils ultimately determines the final performance of the TF magnet in terms of alignment. When the coils are potted in the case, the results of all previous efforts up to that point are locked in place. Final machining of the case bolting flanges and selective assembly will still allow some adjustability of the octants relative to each other, but the coil positions between coils within an octant are fixed from the moment of the first case potting operation. For this reason coil position will be constantly monitored to assure that accurate positioning is maintained before and during case potting. Additional concerns regarding case distortion are causing some risk mitigation by consideration of alternative manufacturing techniques. The attachment of the coil cover and the chimney may be a bolting operation or a welding operation depending of the results of welding development at B&W NED Mt. Vernon Works. The driving emphasis of this effort is to place the coils with extreme precision, capture them at those precise locations, and accurately capture the as-built coil position data for engineering modeling and analysis.

4.1 REQUIREMENTS

The most stringent of the requirements of the TF Octant Assembly Process is directly related to the field error. Refer to Section 3.1 for a detailed presentation of coil positioning requirements. To achieve the allowable error requires extreme cleanliness levels, precision assembly, and special inspection techniques. Consider the diameter of a human hair is on the order of $0.015''$ and then relate that to the allowable positional error of these large coils including measurement error of $\pm 0.005''$. Obviously, every facet of manufacturing must be tightly controlled to achieve precision on this order of magnitude.

4.2 PROCESSES

Figure 11 and Appendix II contain the process details regarding the TF Case Assembly process. Not included in that information is the reasoning involved in selecting the processes used and their order. Coil positioning strategy, the need for partially potting the coil in the case (adopting a 2 stage potting operation), and the splice block attachment considerations are discussed.

The strategy of using common coil positioning and placement techniques as shown in Figure 10 is driven by the tight coil position requirements. Once the coil has been properly prepared, the insertion process is straightforward. With the reference surfaces on the coil inside

diameter and the corresponding case pads, it is simply a matter of slowly lowering the coil into place while maintaining contact at those three pad locations. Inspection and insertion iterations will be required but the process allows the best possible precision. Since B&W has a crane with a super slow speed on the cable winch, it is possible to lower the coil without an elaborate and expensive assembly stand. The end result of this process is a precisely placed coil in the TF case.

This need to capture the coil so precisely is also the driver behind the partial potting of the coil into the case before rotating it so the chimney is in the up position. If the coil had merely been shimmed in place, the upending operation might cause load distribution changes resulting in small shifts in the coil position. Quantifying and controlling these shifts would be difficult if not impossible. The partial potting operation will firmly lock the coil into the case before the case is rotated to vertical. A post partial potting survey of coil position relative to the case fiducials can be performed, since the temporary coil fiducials are still attached. These temporary fiducials are removed just prior to the coil cover being installed. The preparation of the helium stubs to expose the electrostatic shield in the coil stage reduces the finishing operations in the chimney region.

The attachment of the splice blocks at B&W greatly simplifies the operations and reduces risk. The removal of the chrome from the conductor strand is facilitated by having the leads in a vertical orientation for the acid etch. To use acid solutions with the leads in the horizontal with the octants in place in the test cell at Princeton raises safety and product risk questions. The coil assembly workstation at B&W will provide the necessary manipulation of the case to achieve vertical lead orientation. The handling of acids is common at B&W, NNFD. The facility operates acid baths for pickling components and recovery. All aspects of acid use are controlled including procedures, safety equipment, training, process controls, and on-site waste treatment. The performance of the splice block attachment at B&W allows for greater capacity for inspection of the splice block attachment using X-Ray or ultrasonic inspection. Having these operations done prior to shipment of the octants means that the installation operations can be carried out more quickly. The hazardous nature of operations involving acids would most certainly require safety plans resulting in restricted operations in the test cell during the splice block installation. By performing the work at B&W, the impact of this splice block installation is eliminated. From a performance stand point, B&W is required under Phase II of the contract to prepare a draft installation procedure. If the splice block attachments were made at PPPL and there was a problem, determining the root cause of the problem would be more difficult. Was the problem personnel related, procedure related, equipment related, or simply communication related? Obviously, if the work is performed here, the personnel drafting the procedure would be more familiar with the personnel performing the work, the support systems available, and existing B&W NNFD methods designed as support to the proposed process.

4.3 TOOLING & EQUIPMENT

The tooling and equipment included in this section are the Case Assembly Workstation, Coil Insertion Fixture, Laser Tracker System, Epoxy Potting System, Track Welding System, and the large Farrell machining center. The Laser Tracker System was discussed in some detail in Section 3.3.3 and the large machining center was described in Section 2.3.1.3. Since those items were previously discussed, subsequent description of them will be limited.

4.3.1 Case Assembly Workstation

The case assembly workstation is the stand which holds, orients, and restrains the octant case during the assembly process. The conceptual design of this piece of tooling is still pending but is largely dictated by its function. During case assembly processing, the case must be rotated with respect to all three axes. The basic assembly angle must be rotated so that the chimney are is raised 5° for the partial potting of the first coil. Then, the case must continue that rotation to 90° and tilt to put the coil chimney opening top dead center. Next, the coil must be repositioned to insert the second coil. Because of the addition of the Case Cover Assembly, the angle the stand forms with the horizontal must be altered. Subsequent angles of rotation and tilt must be modified to accomodate the angular change. The level of complexity of the position changes and the interface of the fixture with the TF case is still under consideration.

4.3.2 Coil Insertion Fixture

Figure 12. Conceptual Design of Coil Insertion Station

The coil insertion fixture is a precision system to accurately place the coil in the case, assuring contact between the G-10 locator pads on the case and those on the coil. This contact must be in a controlled consistent fashion to assure repeatability. This is especially important because the tight tolerances depicted in Figure 5. TF Coil Positional Accuracy Requirement.

The crane system provides the precision required for the movement in the verticle axis. The lifting fixture connection to the crane hookup must provide a means for leveling the coil, to assure simultaneous loading of the locator pads. Laser tracker targets may be added to the lifting fixture for leveling the fixture.

The lifting suspension straps will probably be

sacrificial given the tight clearance between the coil and case. The cost of the straps will not be very high. The exact number and position of the straps will be determined during the detailed design drawing.

4.3.3 Laser Tracker System

The laser tracker system will be moved to the assembly with the coil. The system provides the primary method of inspecting the inserted coil's position relative to the case fiducials. It will also be used in subsequent set ups for machining the case and assembling the octants.

4.3.4 Epoxy Potting System

The epoxy case potting system will be designed to utilize mixing, piping, and pumping systems also used in the coil VPI system. This will reduce tooling costs without hampering throughput, since the constraining resource is the coil reaction furnace. Obviously, four major fixtures specific to the case design are also required.

4.3.4.1 Generic Epoxy Potting System Components

The use of the same basic system greatly reduces tooling costs, training costs, and maintenance costs. The piping, pumps, and mixers will serve both the coil VPI and case potting, saving the program money. Reference SDRL-22 for more detail on the VPI system.

4.3.4.2 Design Specific Tooling

There are five major pieces of contract tooling required for potting the coil in the case. These are the Case Potting Manifold, the Temporary Left Coil Cavity Cover (for partial potting the coil), the Temporary Right Coil Cavity Cover, the Left Coil Chimney Cover (for both partial and final potting of the coil), and the Right Coil Chimney Cover. The conceptual design of this tooling is awaiting the decision of welded versus bolted coil covers and chimneys, as that decision will determine the case interfaces available.

4.3.5 Track Welding System

The track welding system is a candidate for case cover welding should the design specify a cover weld. Obviously, this is a function of the findings of the weld development as laid out in Section 2.4. The track welder will simply be a welding head riding around on a track shaped to follow the contour of the weld seam. The system would use a mechanical seam reference system to assure seam tracking is properly achieved during welding. The system would utilize existing camera and data collection systems to capture process performance data.

4.3.6 Case Heating System

The case heating system would be a custom adaptation of an off the shelf item. The system envisioned would use flexible heater belts similar to those used to perform stress relief on large welded vessels. The unit would be wrapped with insulation on the side opposite the case to reduce heat loss through radiation. The control system for the heater unit will possess a thermocouple

feedback system and a proportional control mechanism to facilitate a controlled heating of the case to activate the epoxy potting compound.

4.3.7 Large Milling Center / Final Machining Fixture

The large machining centers described in Section 2.3.1.3 are capable of doing the final machining of the coil covers and case assembly. The conceptual design of this fixture is dependent upon the processes functional direction. If the entire TF system is machined and assembled on a machining center, the fixture will necessarily be significantly larger and more complex than if the octants are machined and shipped without the assembly fit up. As the design evolves in Phase II, the machining development program will provide answers as to the need for final fit up prior to shipment.

4.4 TECHNICAL CONCERNS

The technical concerns regarding the octant assembly processes echo the previous concerns of alignment and case distortion but add two new concerns, voids and conductor damage. The coil alignment issue has been address previously, but new operations add additional sources of variability. The case distortion concerns may well disappear if the coil covers and the chimney are bolted. The remaining concerns are manageable.

4.4.1 Coil Alignment

The final machining of the TF cases assembly is the last operation directly affecting TF magnet coil alignment. The only other source of misalignment is assembly error in the test cell. To insure the tightest posible control is maintained over this operation the laser tracker system will be shipped to MT. Vernon to aid them in their set-up. Machining development, the 1/4 scale mock-up, and the prototype case machining should identify any process weaknesses so they may be addressed early in the program.

4.4.2 Case Distortion

The risk of distortion, due to coil cover welding and chimney box welding after coil insertion, is reduced since the structure has been annealed just prior to its shipment to B&W. The presence of the fiducials on the case simplifies the recognition of any distortion which might occur. Welding passes at selective locations on the case can be made to correct possible distortion. Should distortion during case cover or chimney box welding prove to be a significant problem, then a bolted cover and chimney design may be employed instead. Design analysis has shown that bolted joints in these areas of the case would be adequate. Distortion effects will be further studied during Phase II of the contract during the fabrication of the 1/4 scale case mock-up.

4.4.3 Voids in the Potting Resin

During the potting of the coil in the case, air bubbles may be trapped in the resin. These air bubbles will become voids which affects the distribution of stresses within the epoxy potting. If these voids are large enough, they could cause cracking of the potting and damage to the coil.

Careful orientation of the case will provide a clear bubble path to avoid bubble entrapment during curing. The work on the prototype magnet will qualify this process.

4.4.4 Damage to Conductor During Attachment of Splice Terminators

The Nb₃Sn conductor is extremely sensitive to strain. During the splice terminator installation preparations, the conduit is removed to expose a length of conductor three feet long. Given the fragile nature of the strand, the conductor must be protected at all time. All handling and process steps will be designed to protect the strand. The leads will be supported and protected with support fixtures at all stages of production.

5. APPENDIXES

5.1 APPENDIX 1, TF CASE FABRICATION PROCESS PLAN

TF OCTANT CASE FABRICATION PROCESS PLAN

(Preliminary)

Ref. SK-TPX 9130-2 for sub-assembly components

1. Set-up fitting & welding fixture per SK-TPX 9130-WF (ref. Figure 13).

MID SPAN FITTING & WELD FIXTURE

SKETCH * SK-TPX 9130-WF

Figure 13. Central Forging Welding Fixture Concept (SK-TPX 9130-WF)

2. Set MK1 central forging (ref. SK-TPX 9130-2, Figure 15) into fixture & clamp in place (fixture is machined to locate MK1 on octant centerline and to maintain 22-1/2° centerline to centerline coil location).
3. Set (2) TF coil gauge/fixture (Ref. SK-TPX 9130-T-1, Figure 14) into fixture. Align dowels and bolt into place, (SK-9130-T SHT 1). These gauges maintain coil centerline and octant centerline alignment through-out fitting and welding the mid span assembly.

4. Using the coil gauges for alignment fit the (2) MK2 coil case back plate assemblies to the MK1 forging.

5. Weld the backside of the MK2/MK1 welds.
6. Penetrant Test the MK1/MK2 welds & inspect (backside).
7. Fit the MK4 top & bottom assemblies into place.
8. Weld the MK4 assemblies to the MK2/MK1 sub-assembly.
9. Penetrant Test the MK4 welds & inspect.

10. Fit the MK5 top & bottom assemblies into place. The cover plates (Ref. SK-TPX 9130-5, Figure 17) for the top & bottom assemblies will not be fit & welded at this time. The cover plates will be assembled after the cooling tubes are installed.

11. Weld the MK5 top & bottom assemblies into place.
12. Penetrant Test the MK5 welds & inspect.
13. Fit the MK6 assemblies into place.
14. Weld the outside welds.
15. Penetrant Test the MK6 outside weld & inspect.
16. Fit the 4 pcs that make the MK3 assembly into place.
17. Weld the outside welds including the (4) butt welds in the MK3 assembly.
18. Penetrant Test the MK3 welds & inspect.

19. Remove the mid-span weldment from the fitting & weld fixture and remove the TF coil gauge/fixture.
20. Position the weldment on a flat surface & complete all required inner coil case welds for (1) of the coil cases.

21. Penetrant Test completed inner coil case welds & inspect.
22. Reposition the weldment & complete the inner coil case welds for the remaining coil case.
23. Penetrant Test completed inner coil case welds & inspect.
24. Set weldment on flat surface and fit all coil case cooling tubes& weld tube straps.
25. Pressure test all completed cooling tubes. Attach test equipment & seal all tubes at locations external to the weldment.

26. Inspect & verify pressure test.

27. Fit & weld outer cover plate to the top & bottom MK5 inner coil structure.
28. Penetrant Test final MK5 cover plate weld & inspect.
29. Set completed weldment into mid span fitting & weld fixture per SK-TPX 9130-WF and bolt & dowel the TF coil gauge/fixture into place. (SK-TPX 9130-T-1).
30. Inspect & verify clearance between the coil cases and the TF coil gauges.
31. Rework weldment for gauge clearance if necessary.
32. HBM with rotary table required. Set-up on HBM per SK-9130-LO (ref. Figure 19). Permanently establish and identify on all accessible surfaces the horizontal and vertical center lines for the octant assembly. Drill & dowel tooling bar for locating centerlines at their intersecting point in the opening between the top & bottom MK5 intercoil structures. Drill & ream tooling holes to assure permanent centerline locations.

- ① CENTRAL FORGING - 1 REQ'D.
- ② COIL CASE BACK PLATE ASS'Y. - 2 REQ'D.
- ③ COIL CASE INNER WALL ASS'Y. - 2 REQ'D.
- ④ INNER INTERCOIL STRUCTURE TOP & BOTTOM - 1 REQ'D.
- ⑤ OUTER INTERCOIL STRUCTURE TOP & BOTTOM - 1 REQ'D.
- ⑥ COIL CASE OUTER WALL ASS'Y. - 2 REQ'D.

SKETCH * SK-TPX 9130-2B

Figure 18. TF Case Assembly Sketch (SK-TPX 9130-2B)

- 33. Inspect & verify centerline location.
- 34. Load weldment on furnace car and support to prevent distortion.
- 35. Heat treat weldment at temperature for 6-8 hours to remove welding stresses.
- 36. Clean & inspect weldment after heat treat.
- 37. Using tooling holes established at step 32 as fiducials, apply G-10 locator pads. These pads will be of sufficient thickness to allow machining the pads to achieve correct coil location within the coil case.
- 38. Set-up the octant mid-span weldment on the machining fixture. Using the fiducials, machine the 1/2" of stock from face of the coil case and machine the G-10 pads to thickness to obtain proper coil position.
- 39. Inspect on the machine.

40. Reposition the weldment for machining the other coil case and repeat steps 38-39.

5.2 APPENDIX II, TF CASE ASSEMBLY PROCEDURE

ACCELERATOR AND MAGNET SYSTEMS	TF CASE ASSEMBLY PROCEDURE	OP TPX-00004 08/09/95 Rev. 00
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SCOPE

This procedure establishes the method for installing two Toroidal Field (TF) superconducting magnet coils into a TF Octant Case for the Tokamak Physics Experiment (TPX) for Princeton University.

GENERAL NOTES

1. For information regarding safety and proper use of any applicable chemicals, consult the Material Safety Data Sheet (MSDS). These sheets are available from the foreman.
2. All chemicals, when not in use, are to be stored in an approved storage container.
3. All waste (i.e. rags, chemicals, etc.) are to be disposed of properly, in accordance with company policies.
4. Safety equipment (i.e. gloves, safety glasses, filter masks, coveralls, etc.) are to be worn when applicable. Machine guards should be in place during winding.
5. Precautions are to be taken to maintain the cleanliness of the environment and individual parts. Coils should be covered during idle periods, welding, and machining. Lint-free gloves should be worn when handling the conductor to avoid leaving fingerprints.
6. Nb₃Sn superconducting strand is brittle and fragile after reaction. Excessive bending and twisting of the strands will damage the strands. Damage to the strands will result in poor magnet performance.
7. If any unusual conditions are observed, immediately contact the supervisor.

PURPOSE

The purpose of this procedure is to assemble two insulated TF coil into a TF case which subsequently will be transported to PPPL for final piping and integration. This process follows the TF Coil Cleaning, Insulation, and Vacuum Pressure Impregnation Procedure.

SUPPORTING DOCUMENTS

The following documents form an integral part of the TF Case Assembly Procedure:

Document Name	Document Number
TF Welding Procedure (Case Welding Addendum)	(TBD)
TF Case Design Drawing	(TBD)
Cleaning Procedure	(TBD)
Material Handling Procedure	(TBD)
QA Acceptance Test Plan (ATP)	(TBD)
QA Verification Test Plan (VTP)	(TBD)
Conductor Splice Termination Installation Procedure	(TBD)
TF Conductor Splice Procedure	(TBD)

ORIGINATOR: Henry M. Bell	DOC ID: 13-950727-BW-HBELL-01	DATE: 8/7/95
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OPERATING PROCEDURE

NOTE: Two coils and a TF octant case must be inspected, released, and matched prior to beginning this procedure.

1. Issue released insulated TF Coil. Place coil on horizontal work surface with the coil leads in the vertical plane with the octant to octant lead (designated lead 1 throughout this procedure) in the upper position. The surfaces to be prepared are those that reference off the case. Attach three fiducials to serve as a reference for inspection.
2. Have an inspector perform the necessary inspection (eddy current is the current baseline inspection method) to establish the position of the conductor within the coil winding. From this inspection data from TBD points around the coil, a best-fit plane will be established to approximate the centerline of the winding. Using this coil centerline data and inspection data from the TF Octant Case, the coil will be modeled to determine the height of G-10 locator pads which will interface with the case.
3. Lift the coil so that the octant to octant lead is in the lower position. With the coil in the horizontal position, solvent wipe coil at locator pad locations. Prepare coil surface, as required, to receive glue and locator pads. Install locator pads.
4. Have an inspector survey the locator pads. Handwork, as required, to achieve final pad height dimension. Solvent wipe coil to remove G-10 fines. CAUTION: A filter mask should be worn during handwork involving G-10.

Figure 20. Left Coil in TF Case

5. Using Coil Lifting/Positioning Fixture, carefully lower and align the coil in the proper position in the case (see Figure 20). **(Note: Exercise extreme caution while handling reacted coils. The leads of the coils are extremely sensitive to damage and should not be used as handles.)** Position the coil in the case by referencing the coil fiducials. Have a QC Inspector verify the coil position and transfer the coil's positional data to the fiducials on the case using the laser tracker system. Place dial indicators in place to monitor coil position during partial potting case positioning.
6. Place temporary shim blocks (coated with mold release compound) around the periphery of the coil to assure no coil movement during positioning of the case for partial potting of the coil. These shims must be positioned above the epoxy level during partial potting, so they may be removed before final potting.
7. Remove Lead Support (Tool No. TBD) and replace with Coil Case Lead Support (Tool No. TBD).
8. Raise the top of the case (lead box end) to a nominal 5° incline. This prevents void formation and provides a heavier deposit of the partial potting epoxy at the base of the coil cavity. The heavier deposit of epoxy in this region prevents movement of the coil during rotation of the case into position for final potting. Check dial indicators to assure that there was no shifting of the coil during the case tilting. Remove indicators.
9. Fit the Left Temporary Case Cover (Tool Number TBD) on the case cavity. Care should be taken to assure proper seal is achieved as part of the vacuum barrier for partial potting of the coil. Special attention is required to assure an adequate seal around the coil leads and lead box opening.
10. Attach the potting plumbing and vacuum lines to the epoxy and vacuum processing equipment. Pump down the coil cavity to assure adequate seal has been achieved.
11. Close epoxy supply line valve.
12. Measure and pour the resin into the resin supplier and the hardener into the hardener supplier. Operator will use vacuum and PLC controls to flow components into the epoxy mixer.
13. Turn on the epoxy mixer vacuum, the epoxy mixer heater and the agitator motor to mix and degas the epoxy. Preliminary plans call for an 11% glass filled epoxy using the same resin used for coil impregnation. During degassing, vacuum pressure shall reach 10^{-3} torr and temperature shall be maintained at the temperature recommended by the resin manufacturer.
14. During the mixing process, observe degassing bubbles through the observation ports. Continue mixing and vacuum at or above 10^{-3} torr for 40 minutes, then check for bubbles. If bubbles are still present continue mixing and vacuum.
15. Once the bubbles have cleared, turn the agitator motor off and continue the vacuum until just before the potting is started.

16. Attach TF Case Flexible Cartridge Heater Belt (Tool Number TBD) around coil case. Dry the coil cavity with dry air at 100° C.
17. Heat the coil cavity to 65° C. The temperature of the coil cavity will be determined by the thermocouples attached to the surface of the case.
18. Immediately turn on the vacuum pump and start pumping out air and moisture vapors as the coil case is cooling.
19. Pull vacuum on the case cavity until two conditions are met.
 - The coil case has cooled to 60° C.
 - The vacuum has reached 10^{-3} torr.
20. With the coil cavity at 60° C and the epoxy degassed and heated to 60° C, gradually open the proportional valve in the epoxy supply line.
21. Flow the resin into the coil cavity from the bottom at a controlled rate. The amount of resin used will be TBD gallons. The rate will be slow enough so that the vacuum pump can maintain a vacuum of 10^{-1} torr.
22. Observation ports in the temporary case cover will allow the operator to monitor the partial potting operation.
23. The hold period (length TBD) of the vacuum cycle will start after the vacuum level has reached 10^{-3} torr. The vacuum will be maintained at 10^{-3} torr or below during the entire holding period.
24. After the hold period, release the vacuum and apply pressure by filling the coil cavity with dry nitrogen at 20 psi. Hold pressure for one hour. Use the relief pressure valve to release the pressure.
25. With the coil cavity filled with dry nitrogen and the circulating fans turned on, turn TF Case Flexible Cartridge Heater Belt on. The exact curing temperature will depend on the resin being used.

NOTE: The temperature gradient within the coil and case is critical. Heat application shall be controlled with a rate of change of case temperature not to exceed 20° C /hr. Controllability of ramp rate shall be (+0 - 5° C) and the tolerance on the temperature setting shall be +/-3°C. The pressure relief valve shall be used to prevent any over pressures during the curing cycle, due to elevated temperature.

26. Once the curing temperature is reached, as indicated by a set of thermocouples on the surface of the case, the coil cavity shall dwell at a set temperature for a specific amount of time. The dwell time and temperature will be as recommended by the resin manufacturer.

27. Gradually decrease the temperature to (temperature TBD), the rate of decrease shall not be more than 20° C /hr.
28. After successfully completing the partial potting procedure, disconnect and remove all epoxy and vacuum plumbing. Disassemble the reusable Left Temporary Case Cover and remove it. Remove the temporary shims from around the coil. And visually inspect the potted coil. Remove the cartridge heater system.
29. Rotate the case until the left coil cavity is once again horizontal.
30. Issue a Left Case Cover Assembly (Refer: TPX Bill of Materials for part number).
31. Solvent wipe coil cavity and Left Case Cover Assembly.

Figure 21. TF Case with Left Case Cover Assembly

32. Position and tack weld Left Case Cover Assembly to the TF Case (see Figure 21), per the TF Welding Procedure (Case Welding Addendum). Visually inspect the tack welds.
33. Seal weld the case cover to the case using a semi-automatic machine weld (partial penetration), per the TF Welding Procedure (Case Welding Addendum).
34. Inspect the cover seal weld, per the TPX ATP.

35. Rotate the coil until the TF Case chimney area is located at top dead-center. Refer to Figure 22. Case Chimney Area Close-up Showing Epoxy Fill Level to see the relative orientation the case must achieve in order to have the plane of the desired final potting fill line be horizontal.

36. Fit chimney area vacuum cover (Tool Number: TBD) in place and seal, carefully sealing around the helium stubs..
37. Attach the final potting epoxy and vacuum lines to the TF case ports.
38. Close epoxy supply line valve.
39. Measure and pour the resin into the resin supplier and the hardener into the hardener supplier. Operator will use vacuum and PLC controls to flow components into the epoxy mixer.
40. Turn on the epoxy mixer vacuum, the epoxy mixer heater and the agitator motor to mix and degas the epoxy. Preliminary plans call for an 11% glass filled epoxy using the same resin used for coil impregnation. During degassing, vacuum pressure shall reach 10^{-3} torr and temperature shall be maintained at the temperature recommended by the resin manufacturer.
41. During the mixing process, observe degassing bubbles through the observation ports. Continue mixing and vacuum at or above 10^{-3} torr for 40 minutes, then check for bubbles. If bubbles are still present continue mixing and vacuum.
42. Once the bubbles have cleared, turn the agitator motor off and continue the vacuum until just before the potting is started.

43. Attach TF Case Flexible Cartridge Heater Belt (Tool Number TBD) around coil case. Dry the coil cavity with dry air at 100° C.
44. Heat the coil cavity to 65° C. The temperature of the coil cavity will be determined by the thermocouples attached to the surface of the case.
45. Immediately turn on the vacuum pump and start pumping out air and moisture vapors as the coil case is cooling.
46. Pull vacuum on the case cavity until two conditions are met.
 - The coil case has cooled to 60° C.
 - The vacuum has reached 10^{-3} torr.
47. With the coil cavity at 60° C and the epoxy degassed and heated to 60° C, gradually open the proportional valve in the epoxy supply line.
48. Flow the resin into the coil cavity from the bottom at a controlled rate. The amount of resin used will be TBD gallons. Refer to the sight glass level indicator on the chimney area vacuum cover to assure adequate coverage. The rate will be slow enough so that the vacuum pump can maintain a vacuum of 10^{-1} torr.
49. Observation ports in the chimney area vacuum cover will allow the operator to monitor the potting operation.
50. The hold period (length TBD) of the vacuum cycle will start after the vacuum level has reached 10^{-3} torr. The vacuum will be maintained at 10^{-3} torr or below during the entire holding period.
51. After the hold period, release the vacuum and apply pressure by filling the area under chimney area vacuum cover with dry nitrogen at 20 psi. Hold pressure for one hour. Use the relief pressure valve to release the pressure.
52. With the top of the chimney area vacuum cover cavity filled with dry nitrogen and the circulating fans turned on, turn TF Case Flexible Cartridge Heater Belt on. The exact curing temperature will depend on the resin being used.

NOTE: The temperature gradient within the coil and case is critical. Heat application shall be controlled with a rate of change of case temperature not to exceed 20° C /hr. Controllability of ramp rate shall be (+0 - 5° C) and the tolerance on the temperature setting shall be +/-3°C. The pressure relief valve shall be used to prevent any over pressures during the curing cycle, due to elevated temperature.

53. Once the curing temperature is reached, as indicated by a set of thermocouples on the surface of the case, the coil cavity shall dwell at a set temperature for a specific amount of time. The dwell time and temperature will be as recommended by the resin manufacturer.

54. Gradually decrease the temperature to (temperature TBD), the rate of decrease shall not be more than 20° C /hr.
55. After successfully completing the final potting procedure, disconnect and remove all epoxy and vacuum plumbing. Disassemble the reusable chimney area vacuum cover and remove it. Visually inspect the potted coil. Seal epoxy ports as required.
56. Handwork the helium stubs to remove excess epoxy and fill any voids. Assure that the electrostatic shield is exposed so it may be properly grounded later.
57. Solvent wipe potted coil's surface.
58. Repeat steps 1 through 57 of this process for the Right Coil preparation and installation into the TF Case, taking particular care that the Left and Right Coils leads are supported constantly and spacing maintained to prevent damage to the leads.
59. Preparation of the coil splice termination for splices between octants will be prepared first. The left hand coil terminations will be made first.
60. Place case on the assembly stand with the coil leads in the vertical plane with the octant to octant lead (designated lead 1 throughout this procedure) in the downward position. Mask the entire case top except for lead 1.
61. Have an inspector scribe a line for final lead plus instrumentation length on lead-1 from the TF Coil, (reference Cut 1 in Figure 23). Then, have the inspector scribe two additional cut-off lines (reference Cut 2 and Cut 4 in Figure 23). The exact location of these lines will be determined through a model-based calculation of the splice location, using coil and case

inspection data.

62. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 1 aligned with the scribe line for Cut 1. Cut through the conduit and remove the conduit and helium flow fitting. Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor. Carefully snip conductor and instrumentation wires and cables to match the conduit length. (NOTE: See General Note 6.)
63. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 1 aligned with the scribe line for Cut 2. Cut through the conduit and remove the conduit. Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor. Carefully snip conductor strands to match the conduit length (reference Figure 23, Cut 3 and General Note 6).
64. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 1 aligned with the scribe line for Cut 4. (Note: Do not proceed further unless adequate time remains in the workday to complete the process steps through splice terminator attachment, step 12.) Cut through the conduit and remove the conduit (reference Figure 23, Cut 4 and General Note 6). Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor.
65. Prepare the exposed conductor and instrumentation for Lead 1 per the Conductor Splice Terminator Installation Procedure. (Note: Lead down position of Lead 1 facilitates the use of a dip etching process.)
66. Install the conductor terminators per the Conductor Splice Terminator Installation Procedure. Solvent wipe lead 1 to remove any dust or other contamination. Note: The octant to octant splice terminators will receive final machining at Mt. Vernon.
67. Have a QC inspector verify splice terminator geometry and quality per the Verification Test Plan (VTP).
68. Wrap coil Lead 1 in protective cushion wrap.
69. Rotate octant so that left coil lead 1 is in the upward position and the left coil lead 2 (the intra-octant lead) of the left coil is in the downward position. Mask the entire octant except for lead 2.
70. Have an inspector scribe a line for final lead plus instrumentation length on lead 2 from the TF Coil, (reference Cut 1 in Figure 23). Then, have the inspector scribe two additional cut-off lines (reference Cut 2 and Cut 4 in Figure 23). The exact location of these lines will be determined through an inspection of the as-built lead positions of the potted coils, the splice terminators, and case inspection data. Any modifications required of the splice terminators will be performed prior to termination installation.

71. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 2 aligned with the scribe line for Cut 1. Cut through the conduit and remove the conduit and helium flow fitting. Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor. Carefully snip conductor and instrumentation wires and cables to match the conduit length. (NOTE: Nb₃Sn superconducting strand is brittle and fragile after reaction. Excessive bending and twisting of the strands will damage the strands. Damage to the strands in the splice region would result in poor magnet performance.)
72. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 2 aligned with the scribe line for Cut 2. Cut through the conduit and remove the conduit. Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor. Carefully snip conductor strands to match the conduit length (reference Figure 23. Conductor Cut-Off Schematic, Cut 3 and General Note 6).
73. Fit conduit slitting / cut-off tool (Tool Number TBD) to lead 2 aligned with the scribe line for Cut 4. (NOTE: Do not proceed further unless adequate time remains in the workday to complete the process steps through splice terminator attachment, ref. step 21.) Cut through the conduit and remove the conduit (reference Figure 23, Cut 4, and General Note 6. Remove any metal chips or debris from cutting operation. Slit and remove the foil protecting the exposed conductor.
74. Prepare the exposed conductor and instrumentation for Lead 2 per the Conductor Splice Terminator Installation Procedure. (Note: Lead down position of Lead 2 facilitates the use of a dip etching process.)
75. Install the conductor terminators per the Conductor Splice Terminator Installation Procedure. Solvent wipe lead 2 to remove any dust or other contamination. Note: Due to their fragile materials, helium isolators will be installed in the Test Cell at Princeton.
76. QC Inspect splice terminator geometry and quality per the VTP. QC Release coil for case assembly.
77. Wrap coil Lead 2 in protective cushion wrap.
78. Repeat steps 59-77 for the right coil. (Note: Splice geometry within an octant may vary due to the adjustments required in the terminators to adjust for variation in lead alignment.)
79. Clean the terminators and conduit in the splice region. Have QC inspect the relative position of the splice terminators for alignment .
80. Remove protective wrap from both splice terminators and perform the splicing operations per the TF Conductor Splice Procedure.
81. Inspect splice joint, per Acceptance Test Plan (ATP).
82. Attach Splice Region Support Fixturing (Tool No. TBD).

83. Position chimney box sides (Ref. Figure 24). Tack weld chimney box sides in place, per TF Welding Procedure (Case Welding Addendum).
84. Position chimney back. Tack weld chimney back to the octant case and box sides in place, per TF Welding Procedure (Case Welding Addendum). Attach a temporary brace to the free corners of the sides to prevent them from springing apart due to weld distortion. --
85. Weld the chimney box sides and back to the case using a partial penetration weld, per TF Welding Procedure (Case Welding Addendum). Weld the vertical seams between the sides and back using a partial penetration weld.
86. Wire brush and solvent wipe weld area.

NOTE: Chimney Sides and Back may be bolted to the TF Case. Chimney design was not complete at the time of documentation preparation. The chimney sides will likely be 2 pieces.

87. Inspect chimney box welds
88. Fit chimney box front and top plates and bolt in place.
89. Inspect & Release TF Octant.
90. Ship TF Case to Mt. Vernon for final machining.
91. Final machine using QC inspection data and fiducials to establish set-up points. The final machining will require all octants to be completed ready for final machining in order to selectively position them relative to each other to minimize magnetic field error. At this point, the final features of the remaining mating surfaces, including the octant to octant splice terminators will be machined.
92. Solvent wipe.

-
93. Inspect & Release TF Octant for shipment to Princeton for Quadrant assembly or assemble Quadrants at B&W, Mt. Vernon Works. Note: Due to their fragile materials, helium isolators, and the associated piping will be installed in the Test Cell at Princeton.

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 33

TF Magnet Coil Verification Test Plan

August 18, 1995

13-950801-BW-JMaloney-01

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PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**Toroidal Field Magnet
Coil Verification Test Plan**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-PLAN-VTP
REVISION 0**

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1. INTRODUCTION

1.1 PURPOSE

This document describes the verification testing to be performed on the Toroidal Field (TF) superconducting coils for the Tokamak Physics Experiment (TPX) under WBS No. 133. Coil verification tests are performed on the production TF coils during manufacture to demonstrate coil integrity and compliance with the TF Magnet Coil Specification (TFMCS (TPX-SPEC-133-0001)). This test plan covers all tests performed on individual coils starting with coil winding and ending with an insulated coil ready for assembly into the octant housing. Component and material receipt inspections are covered in the Quality Assurance Plan (SDRL - 13). All coil verification tests will be performed at room temperature and the data will be submitted as part of the quality assurance documentation. The word 'test' in this document refers to all demonstrations, inspections, and tests as defined in TFMCS.

A correlation between cold testing performed on the prototype coil will be investigated for extrapolation of room temperature coil characteristics to operational performance requirements.

1.2 HIERARCHY

The Coil Verification Test Plan (CVTP) is one of four test plans supporting the TF coil portion of the TPX project. The other related test plans include: Material and Component, Prototype, and Acceptance Test Plans. The combination of all test plans comprise a fully integrated testing approach to the TF magnet system. Each of the test plans covers a unique series of tests and is designed to provide information throughout the design, manufacturing, and assembly process. The CVTP is derived from requirements in the TF Magnet Coil Specification (SDRL 20). Additional requirements are derived from other documents such as the Failure Modes Effects and Criticality Analysis (FMECA- SDRL 23) and Quality Assurance Plan (SDRL-13). A pictorial of the requirements flow is contained in Appendix A. This pictorial shows the relationship between the related test plans, the various documents that feed or reference the CVTP, and the test procedures derived from this plan.

The individual test procedures will describe in detail the step by step process of each specified test. They will include training requirements, equipment, methods, and pass / fail criteria. A Component Fabrication Routing (CFR) will control the activities performed throughout the manufacturing and assembly process. The CFR will contain directions to perform the testing and a reference to the test procedure that is to be used. The integration of the manufacturing sequence with the inspections and tests performed is graphically represented in Appendix B. This flow diagram, referred to as Manufacturing, Inspection, and Test Flow Diagram (MITFD), is contained in this document as well as the Acceptance Test Plan and Quality Assurance Plan.

1.3 SCHEDULE

The CVTP will be submitted with the TF Preliminary Design Review (PDR) data package. It will be presented at the PDR for initial approval and again at the TF Final Design Review for final approval.

Throughout the preliminary and final design phases, the CVTP will evolve with the TF coil requirements. As criteria are established, the test methods and equipment requirements will be finalized, leading to the approval of the individual test procedures.

1.4 TF VERIFICATION FLOW

The Material and Component Test Plan and the Prototype Coil Test Plan shall be executed prior to the CVTP. The CVTP shall be used for production TF coils prior to assembly in the coil case. The Acceptance test plan covers testing from the time coils are inserted in the case through delivery to PPPL and system level testing.

The coil verification tests are scheduled at critical points in the coil assembly process. Appendix B (MITFD) shows the integration of the manufacturing and coil verification inspection steps. The tests are scheduled to provide verification at the earliest point in the assembly of the coil or where further manufacturing processes would impede the ability to perform testing. The reference numbers under the test steps refer to paragraph numbers in this document that indicate the tests performed at each step.

2. GENERAL TEST OBJECTIVES

The purpose of the CVTP is to provide a complete set of room temperature tests which are designed to verify, to the extent possible, the proper functioning of the TF coils before assembly into the coil cases. The CVTP is a living document that is subject to modification as the requirements placed upon the TF coils are modified and further defined. The tests contained in this plan are designed to determine the coil's compliance with the coil specifications and identify material or manufacturing defects at points where corrective actions can be utilized. Notification and Release points, as defined in the Quality Assurance Plan, will be established for specified tests to notify the customer and allow tests to be witnessed. These notification and release points will be established in conjunction with the TPX project.

Source inspection at the vendor's facility and receipt inspection at B&W of CICC and other components is discussed under the Quality Assurance Plan. Topics covered in the Quality Assurance Plan include: vendor qualification, documentation review, specification compliance, product identification, quality, and shipping damage. Duplication of testing performed by the material or component vendor will not be performed unless circumstances warrant. Material and component vendors shall be required to verify and document, that the product being supplied complies with all requirements and specifications.

Reporting will be in accordance with internal quality assurance procedures and will be contained within the CFR data packet. The data packet is maintained throughout the manufacturing and assembly process and contains all manufacturing, inspection, and test data. The CFR data packet is submitted to the customer as part of the end item certification package (SDRL 44). Test failure disposition and reporting will be in accordance with B&W procedure QT9502 titled "Non Conformance Reporting." Pass/fail criteria for each of the individual tests will be established in conjunction with the subcontractor and TPX project and will be derived from design calculations and possible correlation's established during prototype testing.

Appendix C contains a table of documents supplied by LLNL, the TPX project, and other organizations that pertain to the tests described within.

3. TEST IMPLEMENTATION

This section describes the initial set of tests that are to be performed on the TF coils along with the requirements, methods, and equipment. These tests have been defined and selected by the Quality Assurance and Test section with input from the Design Engineering, Systems Engineering, and Manufacturing Engineering sections.

Attached as Appendix E, is a coil verification test matrix that contains detailed information concerning: the test to be performed, requirements and the specifications that the tests were derived from, the equipment and sensitivities required to conduct the test, and the data derived from the tests. The test matrix has been designed as a reference tool to identify and detail requirements concerning the implementation of the CVTP. The matrix-assists in the planning of the individual tests by establishing the testing inputs i.e.: specific tests to be performed , identification and location of derived requirements and rationale (columns one through four). Based upon the input requirements, the test planning is completed by determining the required outputs needed to perform each test i.e.: the required data, phase of production when tests are performed, location of where tests are performed, equipment required to perform tests, and instrument sensitivity.

Tests performed at the manufacturing site will be performed by trained QA & Test technicians in accordance with approved test procedures. All tests, processes, and procedures will be exercised on dummy coils and mockups produced to verify equipment operation prior to use on the prototype coil or any production coils.

3.1 COIL INSULATION INTEGRITY

3.1.1 General

The TF magnets are, in general, dc coils that experience high voltage surges during rapid discharge. The TF coil turn to turn, layer to layer, and coil to ground insulation are to be tested after the coil has been wrapped with polyimide tape and glass tape and again after it has completed the initial vacuum / pressure impregnation (VPI) cycle. The initial testing will be performed prior to VPI with the dry wrapped insulation. At this stage in the manufacturing process, reduced voltage test levels will be used. The purpose of this test is to allow the detection of gross faults at a point where corrections can be made. The coil will then undergo two separate VPI cycles prior to being installed in the TF case. The first VPI cycle will impregnate the coil matrix after which a layer of glass fiber and the conductive ground wrap shall be installed. The second VPI cycle will impregnate the glass wraps and the conductive ground wrap to secure it in place. The insulation must withstand the steady state operational voltages as well as the higher level transient voltages created by the rapid current discharge during a quench. The maximum voltage generated due to quench is estimated at 15 kV dc (ref.: TPX-STND-001) across the TF bus leads, and ± 7.5 kV dc with respect to ground.

3.1.2 Method and Acceptance Criteria

An in-process insulation verification technique shall be investigated during Phase II for compatibility with the process of insulating the coil prior to VPI at a point where repairs easily achieved. This technique involves placing a high potential metallic shell around the dry insulation of the grounded cable in conduit conductor (CICC) just after it has been wrapped and before it has been laid in the coil form tooling. The shell will be energized to ~ 4 kV-dc and will be electrically coupled to the individual CICC turn segment through helium gas injected between the shell and the CICC. This test will stress the Kapton and verify that there are no pin holes or tears that would decrease the insulation system of the coil. The energized shell would trail the insulation wrapping head around the coil to detect faults in the turn insulation at a point where it can easily be repaired. This technique is similar to the pin hole detection method successfully used by the SSCL project to test the cable insulation prior to spooling. Coil to ground testing is not possible, prior to completing the VPI cycle, due to a temporary insulating plastic lining in the coil form tooling.

Once insulated, low voltage dc resistance and inductance measurements will be performed to verify that there are no gross faults prior to the use of high voltage measurement techniques. Turn to turn and layer to layer insulation integrity measurements will be made using both an induced voltage and impulse measurement technique. Test voltage levels will be ~ 2900 V (i.e. $2 \times V_{\text{peak}}/16_{\text{coils}} + 1$ kV). Note, induced voltage insulation tests are not possible prior to VPI or after conductive ground wrap installation due to interference with the coil form or ground wrap shield.

B&W is initially recommending that high voltage dc Hipot testing to a level of 16 kV ($2 \times V_{\text{peak}} + 1 \text{ kV}$) only be performed on the insulated mock-up winding, dummy coil, and the full scale prototype winding. For the remaining production TF magnets, coil to ground insulation integrity will be verified through: a) process control during manufacturing, b) dc Hipot testing to 7.5 kV (ref.: TPX-ICDP-42-0001), c) insulation resistance testing <1 kV (sometimes referred to as megger testing). The last test will provide the insulation resistance value which will verify that at an applied voltage of 16 kV, the leakage current should be less than 0.1 mA. The rationale for not performing dc Hipot testing to 16 kV on the production TF coils, is because of the relatively large amount of capacitance within the winding pack. Thus, a TF coil can store a significant amount of charge during these tests. Any failure during this test could result in catastrophic and irreparable damage to the coil. This could result in a significant cost and schedule impact. This test level will be supported through testing performed under the Material and Components Test Plan.

Based upon the rationale stated above, coil to ground measurements will be made with a dc high potential meter to an applied level 16 kV ($2 \times$ quench voltage +1kV) after the second VPI cycle on insulated mock-ups and the prototype coils and 7.5 kV on production TF coils. In addition, all Hipot testing on production TF coils will be limited to < 20 s at peak voltage (~ 4-5 quench discharge time constants). Qualification tests will be performed under the Material and Component Test Plan (SDRL 34) using rented test equipment to determine the need and cost/benefit ratio of Tan δ tests for measuring insulation loss and contamination. The ground wrap to case insulation testing involves the application of a temporary conductive wrap after the second VPI cycle. The ground wrap to case test will use an applied voltage of 1 kV. To pass the tests, the insulation must withstand the test voltages without signs of visual flaws or TBD loss, or 0.1mA leakage current. The tests will be conducted in air at room temperature and pressure. Any repairs made to the conductive ground wrap will be tested with a standard Ohm meter to verify continuity between the original wrap and the repair prior to VPI.

Schedule of Insulation Tests

Test Instrument	Internal or External Test	Voltage	Dry Insulation	After First VPI before conductive ground wrap	After Second VPI
Resistance	I / E	Low	x	x	x
Inductance	I	Low	x	x	x
Induced Voltage	I	High		x	
Impulse (Ring)	I	High	x	x	
dc Hipot	E	High	x (w/shell)		x
Tan δ	E	High			x

3.2 COIL ELECTRICAL CHARACTERISTICS

3.2.1 General

Room temperature electrical measurements will be performed on the TF coils to verify the coils proper electrical characteristics. Electrical measurements will be made throughout the manufacturing process to insure the TF coil's integrity. These measurements can only be made after the coil has been insulated due to the metallic contact between turns prior to insulation. The purpose of these tests is to detect gross errors during the manufacture of the magnets and are recommended because of low cost and simplicity. Note, the dc electrical resistance of the coil will change as a result of the reaction process. Since it is difficult to estimate the change in the room temperature resistance as a result of the reaction process, these values will be based upon test results obtained during component and prototype testing.

3.2.2 Method and Acceptance Criteria

Standard, low current, four wire methods will be used to determine the electrical resistance of the coil. Pass/Fail criteria will initially be established based upon design calculations of the conducting cross sectional area/ unit length and later verified through material and component tests (see also Material & Components Test Plan). An inductance meter which employs a bridge type measurement technique will be used to determine the inductance and quality factor of the coil. Because a coil's inductance is sensitive to both geometry (through self and mutual coupling) and close proximity permeable material, it will change throughout the winding and assembly process. Pass / Fail criteria will be established for each phase of manufacturing and assembly process based upon initial design calculations, values measured on insulated mock-up windings using dummy conductor (dummy conductor is defined as In-908 conduit with all copper strand) and values measured during full scale prototype winding.

3.3 PRESSURE TESTING

3.3.1 General

The CICC must withstand increased pressure during a quench due to the rapidly expanding helium gas. The pressure can exceed 1,300 psi (Y. Lvovsky: B&W private communication) in turns farthest from the helium inlet / outlet. The ability to withstand the high local pressures shall be verified through analysis and CICC vendor tests. The magnet manufacturer will test the CICC to a pressure of 370 psi, which is equal to the pressure relief valve settings of the inlet manifold.

3.3.2 Method and Acceptance Criteria

Once assembled, the components will undergo pressure testing to ensure that they are able to meet the required pressure specifications. The pressure testing will be performed by plugging the helium stubs and pressurizing the conduit. The CICC must hold a 370 psi charge with <TBD liters/sec leakage to pass the test. Leaks will also be located using sonic detection and helium "sniffer" detection methods. In addition, by individual plugging of the helium stubs one can verify a consistent flow rate (for a given inlet pressure) among pancakes with similar pipe conductance's. Consistency between similar windings should be within ~5 -10% of each another.

3.4 HELIUM LEAK TESTING

3.4.1 General

Leak testing will be used throughout the manufacturing process to verify welds and closures to ensure that they can maintain the vacuum or pressure levels specified without any leaks over the stated amounts.

3.4.2 Method and Acceptance Criteria

Standard methods of vacuum helium leak detection may not be suited for use on CICC due to its cable density, lengths, and size (i.e. small pipe conductance). However, helium leak detection methods will be investigated on helium stub weld mock-up samples to verify if this technique is suitable. It is possible that the CICC pipe conductance is so small (thus the virtual leak is small) that evacuation on a local scale is still possible. If helium leak detection techniques are not feasible, methods of leak detection using positive pressure in the CICC with an acoustic pickup and/or detection wand on the outside of the coil will be investigated under the Material and Component Test Plan. The acoustic test involves pressurizing the CICC to TBD psi and through the use of a sensitive acoustic microphone, detect the sonic emissions created by the pressurized gas escaping through cracks or holes. This test method can detect leakage levels of TBD and can locate the general vicinity of faults in an un-insulated coil. The hand held wand method draws in air from around the un-insulated coil pack and analyzes it for helium content. Investigation of these detection methods will be explored under the Material and Component Test Plan for their sensitivity and feasibility with CICC leak detection.

3.5 FLOW IMPEDANCE

3.5.1 General

The CICC in the TF magnet is the cooling channel and must sustain a predetermined coolant flow rate in order to maintain operational temperatures. Various operations, such as the attachment of helium stub tubes, have the ability to constrict or disrupt the flow in the CICC.

3.5.2 Method and Acceptance Criteria

Flow through conduit can be accurately correlated between largely different flowing conditions given equivalent Reynolds numbers. For the TF CICC at room temperature flowing conditions, pressures in excess of 6 MPa would be required to achieve an equivalent Reynolds number to that of the actual steady state flowing conditions. An alternative approach is to base the warm test flow on standard flow equations using empirical correlation of friction factors derived for CICC. The friction factor correlation used by E. Tada (reference 13 appendix C) gives good results for Reynolds numbers between 10^2 and 10^4 ; a range which is compatible with the actual flow conditions. The test fluid must have a sufficiently high density to viscosity ratio in order to attain the minimum Reynolds numbers given above. Excluding LN₂ cooled fluids due to cost considerations, the most appropriate choice of a testing fluid at room temperature conditions is gaseous argon. In this test, gaseous argon will flow through the entire coil. The coil will be connected and tested in the same manner as during operation, with multiple inlet and outlet ports. Tests will also be performed to determine flow matching between coolant paths. This test method and the acceptance criteria will be investigated and established under the Material and Component Test Plan during trials on dummy and prototype conduit and conductor.

3.6 INSTRUMENTATION

3.6.1 General

All TF coil instrumentation will be tested at time of installation to ensure proper function prior to continued manufacturing processes. The instrumentation will be again tested after any major manufacturing operation that has potential to damage the instrumentation. TF coils will only contain voltage taps and quench detection fiber optics during the coil manufacturing phase. At present, there are no plans for the installation of strain gages or temperature sensors on the individual TF coil prior to octant assembly.

3.6.2 Method and Acceptance Criteria

The co-wound voltage taps shall be tested for resistance and inductance. Standard four wire resistance techniques will be used to measure the resistance of the wire. The inductance of the tap wires, that are continuous through the CICC, should equal that of the coil. Time Domain Reflectometry (TDR) shall be investigated under the Material and Component Test Plan for locating the voltage tap's internal termination in relation to the end of the coil. Throughout the coil manufacturing process the tap wires shall be re-measured to ensure that no damage has occurred. The re-measured values must fall within $\pm$ TBD tolerance to pass.

The co-wound fiber optic cable shall be tested with a fiber optic test meter to determine distance from the end of the fiber to the mirror installed during cabling. The distance must be with TBD of the incoming inspection to validate that no damage has occurred.

Failure to meet the specified acceptance criteria will result in non-conformance disposition procedures.

3.7 Nb₃Sn Conductor Characteristics

3.7.1 General

The purpose of the test is to verify the current carrying capacity and ac loss characteristics of the superconducting strand under operating temperature and magnetic field conditions. Critical current measurements will be performed on randomly extracted Nb₃Sn strands. Strand verification testing is intended to verify the reaction cycle and proper superconducting characteristics since only the prototype TF coil is currently scheduled to be cold tested. Production coils will not be cooled or energized until after they are assembled in the reactor at the TPX project, unless optional octant cold testing is performed.

3.7.2 Method and Acceptance Criteria

A total of ten strands (ref.: R. Kunz B&W private communication) will be extracted from both ends of the CICC after winding and prior to reacting of each TF coil. The number of extracted strands to be tested represents a compromise between the statistical requirements for testing and minimizing test costs. The un-reacted strands will be fixtured using the "barrel method" in the same configuration used by the TPX project during cable qualification testing and reacted in the same reaction cycle as the TF coil. The reacted strands will be tested for their current carrying capacity and ac loss characteristics under various magnetic field, strain, and temperature conditions to assure that the conductor meets the specification. The values for applied magnetic field, strain, and temperature along with the testing procedures and standards shall be in accordance with those used by the TPX project during cable qualification testing. Pass/fail criteria for the strand measurements will be established by the TPX project during cable qualification testing.

3.8 Dimensional Inspection

3.8.1 General

Design tolerance dictates that dimensional measurements be made on the coil throughout the manufacturing process to ensure proper forming, alignment, and magnetic field.

3.8.2 Method and Acceptance Criteria

Various methods will be used to make dimensional measurements. Dimensional measurements on the coil shall consist: of in-situ radius and conductor length as provided by the winding machine instrumentation and spot checked by inspection, turn to turn gap measurements, outer coil envelope size, flatness, and alignment, and coil position within the insulation for transfer to case fiducials. All tooling will be pre-inspected prior to use to ensure proper tolerances are maintained. Pre-reaction measurements shall be compensated for reaction shrinkage. Measurement instruments shall include: eddy current for insulation thickness, custom radial gages, optical survey, calipers, micrometers, squares, and other calibrated miscellaneous measurement equipment. Dimensions must be within drawing tolerance for acceptance without waiver.

3.9 WELD INSPECTION

3.9.1 General

Various welds on the CICC require tight process control, monitoring, and inspection. The attachment of the helium stubs to the CICC require full penetration welds of dissimilar metals without over heating the conductor and, the attachment of the splice block halves require closure welds around the reacted CICC ends.

3.9.2 Method and Acceptance Criteria

In addition to the process monitoring described in §3.13, welds on the CICC will undergo standard die penetration tests to verify that there are no surface cracks that would effect the performance of the connection. The helium stub attachment weld will also be subjected to ultra-sonic (UT) inspection to verify that the weld attained full penetration and that the interior of the weld is structurally sound. These tests will be performed after the weld has been completed and before any further coil processing has occurred. A crack or imperfection detected by these inspection techniques will be reviewed by engineering with formulation of corrective action through a material review board and non-conformance reporting procedures.

In process inspection of the welds on the CICC will involve the use of temperature sticks. This process uses a temperature sensitive film that is placed on the outside of the CICC at a specified distance from the weld area. If the temperature of the CICC exceeds a predetermined maximum temperature, the film will melt. The maximum temperature will be selected through thermal analysis to ensure that the surface of the conductor does not exceed 400° C.

The use of liquid nitrogen to locally cold shock welds shall be investigated under Phase II for use on production coils.

3.10 CICC CRACK DETECTION

3.10.1 General

Various forces will be acting on the conduit during cool-down, operation, and warm-up that include thermal contractions / expansions, Lorentz forces, and quench pressure exceeding 1,300 psi. The CICC manufacturer shall test or qualify the conduit, in accordance with the CICC specifications, prior to delivery to the magnet manufacturer. The most likely causes of cracks in the conduit during magnet manufacturing are from the reaction process causing cracks in welds, such as the helium stub attachment, and Stress Accelerated Grain Boundary Oxidation (SAGBO). Therefore, crack detection will be performed on the CICC after it has been formed and reacted but before it has been insulated. This allows for early detection of cracks and application of corrective actions, prior to further investment in the coil and thus reducing overall program risk. The method selected must be able to detect cracks through the thickness of the conduit.

3.10.2 Method and Acceptance Criteria

Various methods, investigated under the Material and Component Test Plan, will be employed to determine defect locations in the conduit prior to and after conductor reaction. During tests, precautions will be taken on the post reacted CICC in order to minimize strain on the conductor. Turn by turn crack detection can only be performed as the coil is transferred from the hanging fixture to the insulated form. This limited access also limits the detection methods available. Due to this limited access and cleanliness requirements, the most likely method of detection will be Eddy Current analysis (see also Material & Component Test Plan for crack detection test analysis). Defect detection, repair, and verification procedures will be generated and validated through CICC coupon tests. A detected crack will be grouped into one of two categories, long crack (over 0.055"), and short crack (under 0.055"). A long crack can not have a depth equal to or exceeding 10% of the conduit wall thickness. A short crack can not have a depth equal to or exceeding 20% of the wall thickness. Both requirements apply to cracks on both the inside and outside of the conduit.

3.11 CONDUCTOR SPLICE

3.11.1 General

Acceptance testing will be performed on the coil to coil splice joint in order to assure proper functioning of the joint. This test will be conducted after the splice block halves have been attached. The splice joint must maintain its mechanical integrity under the cooldown and energization loads as well as providing a low electrical resistance in order to avoid excessive heating at the junction. The splice joint must also be fabricated in such a manner as to avoid excessive solder buildup which could in turn block or obstruct the cooling channels. The testing of the splice joint will focus on the interface between the superconducting cable and the copper block of the joint. Due to the difficulty of testing, the quality of the joint must be ensured through rigorous process controls.

3.11.2 Method and Acceptance Criteria

Due to the fragile nature of the superconducting phase of Nb_3Sn , mechanical testing of the splice joint as an acceptance test is viewed as detrimental to the coil. NDE tests such as ultrasound are being evaluated under the Material and Components Test Plan (MCTP - SDRL 34) for their merit in determining the percent solder bond to the conductor. Correlation between the mechanical integrity of the splice joint to the percent solder bond will be investigated. This test is described in more detail in the MCTP. Room temperature electrical resistance measurements will be taken only to assure electrical continuity and verification of reasonable values of splice joint resistance. Determination of the splice joints electrical resistance under simulation of operating conditions will be conducted at the material and components level. Flow tests, which will be used to check for solder obstruction, are described in section 3.5.

3.12 VISUAL INSPECTIONS

Visual inspections shall be performed throughout the manufacturing process to verify that the coil appears to be clean and undamaged. The coil will be inspected constantly for signs of damage, foreign particles, and other contaminants. A visual inspection of the color of the CICC will be performed after completion of the reaction cycle. The CICC should not discolor (i.e. remain bright with a high gloss shine) as a result of the reaction process. Preliminary test results from MIT indicate that a slight amber hue is acceptable to assure that there was no oxidation during reaction that would lead to SAGBO. Color tables will be developed under Material and Component Test Plan. Other examples of visual inspection include: checking for debris on the conductor after opening a cooling channel hole, tears in the insulation during wrapping, voids after VPI, handling damage, etc.

3.13 PROCESS VERIFICATION

Process parameters for operations such as welding, winding, reaction, and VPI will be checked prior to starting the process, monitored during the operation, and again verified after the operation is complete. The parameters will be detailed in a component fabrication routing (CFR) document that lists every manufacturing and inspection step performed. This document contains the parameters, procedures, and sign-offs for all process criteria and inspections. Critical parameters will be monitored continuously throughout the operation and may be recorded through the data monitoring / control system of the process equipment. An example of in-process monitoring will occur throughout the reaction process and will encompass oxygen level, temperature, and time to prevent SAGBO effects.

3.14 MAGNETIC FIELD MEASUREMENT

The magnetic field of the TPX project shall be corrected with perturbation coils to levels defined in the GRD. Exact field error tolerance requirements for the magnetic field produced by the TF coil system alone have not been partitioned by the TPX project. There is no scheduled room temperature magnetic field testing of individual TF magnets.

4. CONCLUSION / FUTURE WORK

The CVTP is one of four integral test plans which are designed to evaluate the performance of the TF coils and provide information into the design, manufacture and installation of the TF coils (see also Appendix A). The CVTP is a fully integrated test plan within the TF coil program and is supplemented by the FMECA and the Quality Assurance Plan. In addition, the CVTP is complimented by the lower level detailed verification test procedures, which describe the in process steps of each test. Future work to formalize the completion and integration of the CVTP in the TF coil program will include the following: 1) establishment of pass/fail criteria for tests outlined in coil verification test matrix, 2) periodic update of the CVTP to reflect modifications in design derived requirements, 3) integration with supplemental test plans, i.e. FMECA and Quality Assurance Plan, for a comprehensive TF testing approach, 4) completion of detailed test procedures, 5) determine facility and equipment requirements for testing, 6) develop test technician training programs.

Appendix A

Information Flow Diagram

Appendix B

TF Manufacturing, Inspection, and Test Flow Diagram Legend

Manufacturing operation

QA & Test Inspection and/or test operation

Combined Manufacturing and QA & Test operation

Package & Ship/ or Production Control operations

Customer Release Point

NP

Notification Point

Appendix C

References

1. GRD, GENERAL REQUIREMENTS DOCUMENT
2. TPX-STND-001, TPX STRUCTURAL AND CRYOGENIC DESIGN CRITERIA
3. 13-930319 -LLNL/WHASSENZAHN-01, SYSTEM DESIGN DESCRIPTION TF MAGNETS
4. SYSTEM DESIGN DESCRIPTION, TPX POWER SYSTEMS
5. SOW, TPX TECHNICAL SCOPE OF WORK, TPX MAGNET SYSTEM
6. SDRL - 13, QA PLAN
7. SDRL - 20, TF MAGNET COIL SPECIFICATION
8. SDRL - 23, FMECA
9. SDRL - 32, COIL ASSEMBLY DOCUMENTATION
10. SDRL - 34, MATERIAL AND COMPONENT TEST PLAN
11. SDRL - 35, PROTOTYPE TEST PLAN
12. SDRL - 45, ACCEPTANCE TEST PLAN
13. E. TADA, ET AL, STEADY PRESSURE DROP AND QUENCH PRESSURE RISE IN CABLE-IN - CONDUIT SUPERCONDUCTORS; CRYOGENICS 32:829 (1992).
14. C.M. REY AND K.C. HENDERSON, "AN EXPERIMENTAL INVESTIGATION OF THE APPLICATION OF TIME DOMAIN REFLECTOMETRY TO SSC CABLE INSPECTION," B&W REF. NO. RDD:93:62072-001-001:01, JUNE 1992

Appendix D

TF Magnet Coil Quality Conformance Matrix

(Ref. TPX-SPEC-133-0001)

CVTP Par.	TFMCS Par.		Analysis	Demo	Inspect	Test	N/A
	3.1	Item Definition					x
QA Plan	3.1.1	Prime Item Diagrams			x		
	3.2	Characteristics					x
	3.2.1	Performance					x
3.1 & 3.2	3.2.1.1	Electrical Characteristics				x	
3.3 & 3.4	3.2.1.2	Pressure and Leak Rate Characteristics.				x	
3.5	3.2.1.3	Hydraulic Characteristics				x	
3.6	3.2.1.4	Instrumentation Characteristics				x	
	3.2.2	Physical Characteristics					x
3.8	3.2.2.1	Coil Dimensions.			x		
3.5	3.2.2.2	Cooling Flow Path			x		
3.1	3.2.2.3	Grounding			x		
3.6 & 3.11	3.2.2.4	Lead terminations			x		
TBD	3.2.2.5	Strain Limit after Reaction			x		
	3.2.3	Reliability	x				
	3.2.4	Maintainability		x			
	3.2.5	Environmental Conditions					x
	3.2.5.1	Shipping and Storage Environments	x				
	3.2.5.2	Operating Environments	x				
	3.3	Design and Construction					x
	3.3.1	Materials, Processes, and Parts					x
	3.3.1.1	Material Selection		x			
3.9	3.3.1.2	Weldments		x			
	3.3.1.3	Conductor Winding Process		x			
3.5 & 3.9	3.3.1.4	Helium Stub Installation Process		x			
3.7	3.3.1.5	Conductor Reaction Process		x			
3.1	3.3.1.6	Coil Insulation Process		x			
	3.3.2	Reserved					x
QA Plan	3.3.3	Nameplates and Product Marking			x		
QA Plan	3.3.4	Workmanship			x		
	3.3.5	Interchangeability of Components		x			
	3.3.6	Safety		x			
	3.3.7	Human Factors		x			
	3.4	Documentation					x
	3.4.1	Specifications		x			
	3.4.2	Drawings		x			

App Acceptance

Acceptance Test	Derived From	Test Loc.	Rational for performing test	Phase of Production	
1. Dimensional Inspection	TFMSRD §3.1.2.10	B & W and TPX Site	<ul style="list-style-type: none"> As built key dimensions 	<ul style="list-style-type: none"> Throughout manufacturing After Delivery to TPX Site 	•
2. Coil Electrical Characteristics	TFMSRD §3.1.3.2	B & W and TPX Site	<ul style="list-style-type: none"> Basic electrical properties of coil 	<ul style="list-style-type: none"> Throughout manufacturing After Delivery to TPX Site 	• •
3. Instrumentation	TFMSRD §3.2.1.3.	B & W and TPX Site	<ul style="list-style-type: none"> Verify that installed instrumentation is functioning. Verify instrumentation is electrically isolated from High Voltage components 	<ul style="list-style-type: none"> After installation Upon Delivery to TPX Site System level 	• • • • •
4. Coil Insulation Integrity	TFMSRD §3.2.1.4	B & W and TPX Site	<ul style="list-style-type: none"> Turn to Turn Insulation Integrity Coil to Ground Insulation Integrity 	<ul style="list-style-type: none"> After installation in TF case After Delivery to TPX Site 	• • • • •
5. Structure Insulation Integrity	TFMSRD §3.2.1.5	B & W and TPX Site	<ul style="list-style-type: none"> Ground Plane Insulation Integrity Component Insulation Integrity 	<ul style="list-style-type: none"> After coil and component installation After Delivery to TPX Site 	• • •
6. Flow Impedance	TFMSRD §3.1.2.9	B & W and TPX Site	<ul style="list-style-type: none"> Verify pressure drop through winding does not exceed limit. Verify pancake variability does not exceed limit 	<ul style="list-style-type: none"> After Delivery to TPX Site 	• • • •
7. Helium Leak Testing	TFMSRD §3.3.1.2	B & W and TPX Site	<ul style="list-style-type: none"> Weld integrity 	<ul style="list-style-type: none"> Throughout manufacturing After Delivery to TPX Site 	• •
8. Octant Level Cold Tests	TBD	TBD	<ul style="list-style-type: none"> Cold magnet, structure, and instrumentation data 	<ul style="list-style-type: none"> After completion of Octant assembly 	•
9. System Level Tests	TBD	TPX Site	<ul style="list-style-type: none"> Final assembly certification / calibration 	<ul style="list-style-type: none"> After system assembly is complete 	•

Appendix E

Testing Matrix

Specification Requirement & Source / Test Requirement	Equipment Required	Equipment Sensitivity Required
Per Drawings	<ul style="list-style-type: none"> Misc. 	<ul style="list-style-type: none"> TBD
Inductance ≈ 50.7 mH for single coil Resistance ≈ 0.173 Ω per coil	<ul style="list-style-type: none"> Test Cart system (power supply, volt meter, inductance meter) 	<ul style="list-style-type: none"> Power Supply $\Rightarrow 10$ amp x 2 V LCR meter $\Rightarrow 50.7$ mH Volt meter $\Rightarrow 0.1$ mV accuracy
Do-wound voltage taps- Resistance = TBD Direct wired voltage taps Insulation from case = 16 kV Flow Sensors Strain Gages Fiber Optics Temperature Sensors	<ul style="list-style-type: none"> Volt Meter Current Supplies Fiber Optic Meter TDR Meter 	<ul style="list-style-type: none"> TBD
Turn - Turn = 10V inductive voltage during fast dump - test to 2900 volts Impulse / induced (2x coil +1) (per WBS 42- Power Supplies and Quench Protection) max. Layer to layer = 240V inductive during fast dump coil to Ground >7.5 kV - Quench Voltage - Test to 2x+1=16kV dc Hipot (per WBS 42- Power Supplies and Quench Protection) Ground wrap to case (with ground point lifted) 1 kV dc	<ul style="list-style-type: none"> dc High Potential Meter Tan-Delta Meter Impulse test system 	<ul style="list-style-type: none"> dc Hipot $\Rightarrow 16$ kV production test $\Rightarrow 0.01$ mA current trip Impulse $\Rightarrow 2.9$ kV Tan δ $\Rightarrow 11.3$ kV AC $\Rightarrow 60$ Hz
From assembly to other assemblies >1 kV Helium Isolators >16 kV in GHe.	<ul style="list-style-type: none"> High Potential Meter 	<ul style="list-style-type: none"> dc Hipot $\Rightarrow 16$ KV production test $\Rightarrow 0.01$ mA current trip
ATM inlet - 2-3 ATM outlet SC He 8 g/s in TF coil SC He (7g/s through each winding) Gas Argon Test (11 ATM drop @ 1.71 SCFM per Kelly Dixon)	<ul style="list-style-type: none"> Flow meters Pressure transducers Pressurized Argon supply 	<ul style="list-style-type: none"> Flow meter $\Rightarrow 2$ SCFM, .01 res. Pressure Transducer $\Rightarrow .05$ psi
BD	<ul style="list-style-type: none"> Helium Leak Test system Enclosures 	<ul style="list-style-type: none"> TBD
BD	<ul style="list-style-type: none"> Cold test facility with TBD capabilities 	<ul style="list-style-type: none"> TBD
BD	<ul style="list-style-type: none"> Operational data, power, and control systems 	<ul style="list-style-type: none"> TBD

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT AND MANUFACTURE

Contract B235308

SDRL 34

Material & Component Testing

August 18, 1995

13-950811-BW-JMaloney-05

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PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**Toroidal Field Magnet
Material and Component Test Plan**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-PLAN-MCTP
REVISION 0**

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1. INTRODUCTION

1.1 PURPOSE

This document describes the material and component testing to be performed on Toroidal Field (TF) superconducting coil components for the Tokamak Physics Experiment (TPX). Material and component testing will be used to verify and qualify TPX project supplied and contractor procured materials, processes, and components used in the fabrication of the TF magnet system. The tests will be performed during Phase II of the TPX contract and will emphasize reliability and process criteria. Tests will be performed on mockups, sub-assemblies, components, dummy coils, and coupons to determine compliance with contract specifications. Materials and component testing will place emphasis in the following areas: data required to support design analysis, areas which cannot be tested once assembled, areas that have a significant development effort or support a critical mission of the TPX, components which must withstand repeated cycling. Testing related to manufacturing and process development such as: sheath bonding, reaction coil mock-up, heat transfer tests or conduit bending studies are addressed in the Manufacturing Research Plans and Results (SDRL 37) and Materials and Process Verification (SDRL 40).

1.2 HIERARCHY

The Material and Component Test Plan (MCTP) is one of four test plans supporting the TF magnet portion of the TPX project. The other related test plans include: Prototype, Verification, and Acceptance Test Plans. The combination of all test plans comprise a fully integrated testing approach to the TF magnet system. Each of the test plans covers a unique series of tests and is designed to provide information throughout the design, manufacturing, and assembly process. The MCTP is derived from various sources including: design analysis support, manufacturing process development support, TF Coil Configuration Specification (SDRL 20), TF Magnet System Specification (SDRL 17) Failure Modes Effects and Critically Analysis (FMECA- SDRL 23), and Quality Assurance Plan (SDRL 13).

The MCTP represents the highest level of test planning and will be complimented by individual test procedures which describe in detail the step by step process of each specified test. The detailed test procedures will include training requirements, equipment function, methods and pass/fail criteria.

1.3 SCHEDULE

The MCTP will be submitted with the TF Preliminary Design Review (PDR) data package. It will be presented at the PDR for information and again at the TF Final Design Review for final approval.

Throughout the preliminary and final design phases, the MCTP will evolve with the TF coil requirements. As criteria are established, the test methods and equipment requirements will be finalized, leading to the approval of the individual test procedures.

1.4 TF INFORMATION FLOW

The material and component tests are performed throughout the design and manufacturing phases. The tests are scheduled to provide verification, information, and acceptance at the earliest point in the design of the system or process. The information gained through this testing will be fed back into the design as verification of the designs and limits placed upon materials, components, and processes.

2. GENERAL TEST OBJECTIVES

The purpose of the MCTP is to present a series of tests which are designed to verify the acceptability of the TF coil components process control parameters and magnet assembly procedures. The MCTP is a living document that is subject to modification as the requirements placed upon the TF coils are modified or further defined. The tests contained within this plan are designed to determine the components compliance with item specifications. The tests will be designed to subject the materials and components to conditions similar to, or more strenuous, than they would be exposed to once incorporated in the TF magnet system. Much of the testing is designed to verify the safety margin of the TF magnet system components in order to ensure that they will perform as designed over the specified life when installed in the TPX facility.

Data acquired during the material and component testing will be reported under individual test reports and archived in the configuration management library.

3. TEST IMPLEMENTATION

This section describes the tests that are to be performed on the TF materials and components to verify acceptability, along with the requirements, methods, and equipment. These tests have been defined and selected by the Test and Quality Assurance section with input from the Design Engineering, Systems Engineering, and Manufacturing Engineering sections.

Attached as Appendix B, is a material and component test matrix that contains detailed information concerning: the tests to be performed, requirements and the specifications that they were derived from, the equipment and sensitivities required to conduct the test, and the data derived from the tests. The test matrix has been designed as a reference tool to identify and detail requirements concerning the implementation of the MCTP. The matrix assists in the planning of the individual tests by establishing the testing inputs i.e.: specific tests to be performed, identification and location of derived requirements and rationale (columns one through four). Based upon the input requirements, the test planning is completed by determining the required outputs needed to perform each test i.e.: the required data, phase of contract that data is required, location of where tests are performed, equipment required to perform tests, and instrument sensitivity.

3.1 MATERIALS

Material testing refers to the development of a materials data base to support design and structural analysis of the TF magnet assemblies. The data, when not available from a recognized and published source such as ITER material database, will be developed through testing as prescribed in the Structure and Design Criteria Document (TPX-STND-001). Materials without sufficient historical data will be identified through the Materials and Process Selection document (SDRL 21). The identification of the material and the data that is required will establish the testing that is to be performed. Any testing necessary will be performed at an established material testing facility that maintains the capabilities and equipment to perform the tests in accordance with the Structure and Design Criteria Document. The tests required by the Structure and Design Criteria Document are: Tensile § I-4.1.1, Creep § I-4.1.3, Strain - N Fatigue Curves § I-4.2.2.5, Cracks § I-4.2.3, and Cyclic loading to four times the design lifetime. As of this writing, all materials scheduled for use in the TPX magnet assembly have sufficient existing historical data for design and structural analysis.

3.2 WELDS

Weld testing conducted under the MCTP will be performed in conjunction with weld and process development programs directed by manufacturing engineering. The purpose of conducting weld testing is two fold. First, it establishes a basis for certifying welders and/ or weld procedures for specific types of welds to be performed on the TF magnet assembly. Second, it feeds information back to the design analysis for validation of the model parameters. Qualification and process development weld testing conducted under the MCTP will be performed on both full scale dummy coil and sub-scale manufacturing mockups. In addition, the production welds will also be tested in accordance with both the Coil Verification Test Plan (SDRL 33) and the TF Magnet Acceptance Test Plan (SDRL 45). Tests will be conducted in accordance with the Structure and Cryogenic Design Criteria §I-4.1.1 which states: "Since weld properties are very strongly a function of the metallurgy and technique, the yield and tensile strength will be the minimum of the values resulting from a test lot of at least 6 specimens. The test specimens will be standard tensile test specimens which are representative of a weld joint and in compliance with recognized testing procedures (such as ASTM or ASME). For the test lot to be valid, welder qualification and weld technique must be developed until consistency (test results within $\pm 15\%$ of the average value) is achieved. Residual stresses shall be considered in design and analysis of welds." The weld samples will undergo material properties testing as described in section 3.3. Critical welds that have been identified for testing include:

- helium stub attachment
- case closure
- chimney
- cryogenic feed / return lines
- case cooling connection (copper to copper & copper to stainless).

3.3 HELIUM STUB WELDS

Testing techniques for the helium stub weld are being detailed separately due to the critical nature of the joint, in not only preventing helium leaks, but also avoiding damage to the conductor during the attachment process. Testing will be conducted in conjunction with manufacturing development of the helium stub weld process qualification and supplements the weld testing described in 3.2 . Production helium stub welds will undergo 100% quality assurance testing to ensure that the weld has full penetration, is free from internal and external cracking, and has not heated the conductor above 400°C. The testing performed under the MCTP will develop the methods and procedures for testing production welds.

Heat transfer to the conductor during welding will be measured using a dummy conductor instrumented with thermocouples under the weld regions and outside the conductor. The temperature profiles will be measured during the welding operation and a correlation between the conduit temperature and the conductor temperature will be established. Based upon the information obtained in the process parameter development, production coils will be coated with temperature "sticks" to verify that the maximum allowable temperature was not exceeded during welding.

Once the process parameters for the welding mock-ups are established, samples will be subjected to cold shocking with liquid nitrogen (LN₂). Note, in production welds the LN₂ cold shocking will occur prior to the reaction process and be limited to localized areas adjacent to the weld. After cold shocking the mock-ups, crack detection methods using die penetration will be employed. The purpose of this testing is to establish the method of die penetration to use in the production process. Both visible and fluorescent die techniques are available, however, the visible die method is the least costly of the two. If the visible die method is sensitive enough to locate surface defects smaller than the maximum allowable crack size (~0.010"), no further testing will be required. Otherwise, fluorescent dies will be investigated for their sensitivity.

To verify that the weld was fully penetrated and does not contain internal defects, a non-destructive ultra sonic (UT) detection method will be investigated. UT is a well established technique capable of detecting internal defects within welds, however, because of the complex geometry of the stub weld a development program needs to establish its feasibility. Mock-up samples will be produced using the developed manufacturing techniques. Faults will be created in the mock-up samples to verify that the detection method is capable of locating faults within the weld. In addition to non-destructive evaluation, some of the mock-up samples will under go destructive evaluation and be sectioned to gain access to the inside of the weld for visual inspection. Other detection methods, such as X-ray, will be used to support the process parameter development and establishing the validity of the UT inspection method.

3.4 CASE MOCKUPS

Weld development and manufacturing process development will encompass both large scale and sub-scale case mockups. The purpose of the development program is to understand and limit the effects of weld distortion on the dimensions of the case and reduce the amount of post-welding machining required. This in-turn reduces both cost and schedule risk to the post reacted TF assembly. Testing on mockups and dummy cases will involve weld qualification, as detailed in section 3.3, and dimensional inspection to determine the distortion caused by the welding operations. A large scale three dimensional coordinate measurement system will be employed to accurately measure the effects caused by weld distortion and through process parameter development try to mitigate these effects.

3.5 SUPERCONDUCTOR

The superconductor is furnished to the TF magnet contractor by the TPX project as government furnished material. The requirements specification, testing and qualification of the strand, cable, and Cable in Conduit Conductor (CICC) are the responsibility of the TPX project. Although development of the superconductor is not directly within the scope of the TF magnet manufacturer, the superconductor is the primary component of the magnet assembly and therefore requires the TF magnet manufacturer to participate in the qualification of the superconductor vendor. The level of participation will be limited to reviewing: test plans and data, requirements specifications, quality assurance plans and provisions (including source inspections to insure that vendor processes will provide quality material for magnet manufacturing) and receipt inspection performed at B&W (see also Quality Assurance Plan SDRL 13).

To ensure that the proper superconducting phase of the Nb_3Sn is formed during the magnet manufacture's reaction process, witness samples will be extracted from both the lead and trailing ends of the conductor spool, wound on supporting mandrels (M. Takayasu and R.N. Randall, ITER Critical Current Barrel Assembly) and reacted with the TF coil as described in the Coil Verification Test Plan (SRDL 33) (see also: Manufacturing Research Plans and Results (SDRL 37) and Materials and Process Verification (SDRL 40)). The witness samples will be evaluated by the TPX project superconductor testing lab (MIT). Measurements of both the critical current at temperature and field and ac loss will be performed. Provided the witness samples show satisfactory results, as defined in the TPX Magnet System Specification (ASG94_rev_2), the TF coil will continue through the manufacturing and assembly process.

3.6 STRAIN LIMIT

It is recommended that the post reacted Nb_3Sn superconductor be limited to strains of less than 0.2% (see TPX No. ASG94 rev_2) in order to avoid damage which may limit its current carrying capacity. Because the mechanical coupling between the reacted superconductor and the inside of the conduit is difficult to predict with high precision, it is not directly measurable during production of the TF magnet coils. So as not to exceed this value during the production/fabrication, strain sensitivity studies should be made not only on individual superconducting strands but also on production level CICC. Because it is geometry dependent, several configurations of "as bent" CICC samples should be tested. Taking a synergistic approach (which minimizes testing costs and schedule impact), the "as bent" CICC samples (which simulate CICC production forming operations) will be supplied by the TF magnet manufacturer. These "as bent" samples can be tested in conjunction with the existing splice development test program (see section 3.17). Specific areas of concern of the "as bent" CICC are: lead bending and forming, post reaction insulation wrapping, tight bend radius in winding pack. The samples should be tested at operating temperature, magnetic field and current. CICC strain sensitivity information obtained during the materials and component testing, will be used for production process control.

3.7 CONDUIT

Conduit testing will include: crack detection methods, conduit end and helium stub closures, post reaction color table for determination of SAGBO onset, and characterization of the conduit performance on bending and forming using production tooling. Methods used for crack detection of the CICC must be sensitive enough to detect a crack or defect that is one half the maximum allowable size in accordance with the Structure and Cryogenic Design Criteria (~ 0.010 "). Because of the accessibility limitations, the most likely method for CICC crack detection will be eddy current. A measurement head will be designed that will track along the conduit as it is being unspooled during the insulation process. Mock-up conduit samples with and without known defects will be used to establish the feasibility and sensitivity of the proposed detection system. Mock-up samples will be used at first to develop the technique, leading to final testing with the dummy coil as it progresses through the manufacturing steps.

Throughout the manufacturing process, the CICC will have various gasses pumped through it, vacuum applied externally, and pressures applied internally. The connections on the ends and on the helium stubs require testing to verify that the manufacturing process of attaching the connection did not damage the conductor and the connections meet the pressure, vacuum, and leakage criteria required for conduit testing. Mockups will be made to develop the manufacturing technique. These manufacturing mockups will be tested for the various requirements. Tests will include: elevated pressure to ~ 370 psi internally, standard vacuum helium leak testing, and destructive examination for attachment damage. The closures and process will be refined to the point that they do not introduce any significant error into any production level testing techniques.

Under certain conditions, the Incoloy 908 conduit is susceptible to Stress Accelerated Grain Boundary Oxidation (SAGBO) during the reaction process. In order to avoid this deleterious effect the oxygen partial pressure within both the conduit and the reaction oven, at elevated temperatures, must be limited to < 0.1 PPM. The reaction oven will be constantly monitored for oxygen content throughout the reaction cycle using a residual gas analyzer (RGA). As an additional quality control method to verify that the oxygen level remained below the critical threshold for SAGBO onset, the color of the conduit exterior will be compared to color coding tables developed under this test plan. Oxygen present in the reaction cycle will oxidize the conduit creating a dark hue, whereas the absence of oxidation will be evidenced through a diminishing amber hue. Testing will be conducted on a coupon basis to establish various oxygen concentration levels during a reaction cycle. The color of the coupons will be developed into a color comparison chart. This color chart comparison will be used during the Coil Verification Test Plan for visual verification that the oxygen level in the reaction oven did not exceed the required level.

Throughout Phase I, roll bending and conduit characterization tests were performed to investigate manufacturing methods and equipment requirements. These tests were performed on non-production equipment that might not be indicative of production machinery. Further tests will be performed on production tooling as part of the production machinery qualification to verify that the conduit performs as anticipated. Tests will include: radius measurements throughout the coil, transition bends, lead bends, and dimensional changes due to reaction. All tests will use production level equipment and procedures and will be conducted in conjunction with manufacturing process development and equipment certification.

3.8 COIL ELECTRICAL CHARACTERISTICS

Tests will be conducted on small samples of CICC to determine the electrical resistance per unit length of the conductor prior to and post reaction. This testing will be performed in conjunction with reaction furnace certification and will use production conductor specimens.

Because a coil's inductance is sensitive to both geometry (through self and mutual coupling) and close proximity permeable material, it will change throughout the winding and assembly process. Thus, inductance measurements will be made on the insulated dummy coil to establish inductance values for each step in the manufacturing process. In addition, Pass / Fail criteria will also be established for each phase of manufacturing and assembly process.

3.9 COIL INSULATION

Coil insulation testing will be performed on mockups, practice windings, windings used to certify the proper operation of the production VPI process, and the dummy coil. The testing will verify that production level processes meet the specification's insulation requirements. This testing is not a duplication of the extensive insulation development testing performed under Phase I. Its purpose is to certify production equipment, manufacturing procedures, and develop testing methods and procedures. The insulation samples, practice windings and dummy coil, will be subjected to the same electrical insulation tests as described in detail in the Coil Verification Test Plan (SRDL 33) and will include: impulse testing, dc hipot, induced voltage, Tan δ , and high resistance (megger). Practice windings will be tested to failure in order to gain a better understanding of the insulation margins and most probable locations where faults may occur.

High voltage Tan δ insulation test equipment will initially be rented to investigate cost to benefit ratio of this test. Typically, this type of testing is used to determine high voltage dielectric loss in ac applications. In contrast, the TF coils are in general dc. However, Tan δ tests can also be used in determining insulation contamination characteristics and may be valuable in VPI/ potting process control and qualification.

Investigations will also be made on the mock-ups and practice windings as to the feasibility and success of insulation repair methods and procedures. Repaired insulation will be subjected to similar tests as outlined in Coil Verification Test Plan (SRDL 33) with the addition of testing to failure.

The feasibility of an insulation pin-hole detection method will be investigated. The basic concept of the pinhole detection method is as follows: A metallic cylindrical shell will be placed around the outside of the dry wrap insulated CICC. Helium gas will be injected in the small gap between the shell and the insulated CICC. The helium gas provides electrical coupling media. A high potential will be applied to the metallic shell using a dc hipot while the CICC will be grounded at one terminal. Testing methodology will be developed to determine the optimum parameters such as shell design, gas flow / pressure, shell/conduit spacing, and dc voltage level. The test is designed to stress the dry wrap insulation (Kapton with s-glass) prior to VPI when repairs are still possible. The development of this pin-hole detection system will begin on small mockup samples of conduit with dry insulation and, as developed, will be used on manufacturing trials and the dummy coil winding prior to use on prototype or production coils. In order to minimize the number and size of the voids and resin rich areas within the production VPI insulation, process development control parameters will be investigated and defined. Several manufacturing mock-ups will be destructively examined for location of problematic areas. In addition, high voltage Tan δ measurements will again be investigated for potential use in identifying insulation loss characteristics. It is possible that a correlation between insulation loss characteristics and resin rich/voids can be established. This in turn could be use as a pass/fail characteristic for the production VPI process.

Insulation testing performed on 3x3 and 5x5 mock-ups by Westinghouse during Phase I will be reviewed for completeness. Additional information required to verify design and lifetime requirements on production magnets will be also investigated. Lifetime test requirements include: thermal cycle effects, electrical cycles, insulation aging properties, cyclic stress, and radiation resistance. The lifetime tests performed under the MCTP will depend on the data available and the completeness of Phase I testing. Radiation resistance testing of the baseline insulation scheme will not be performed unless specifically requested by the TPX project.

3.10 CHIMNEY VOLTAGE ISOLATION

Because of the many connections within the chimney region, it is the most likely area for helium leaks. These leaks not only cause thermal insulation problems, but can also cause additional problems with the coil to ground electrical insulation. Therefore, mockup samples using worst case geometries and tolerances of the baseline chimney layout scheme will be constructed using conduit and flat stock. Worst case geometries will be based upon computer simulated electric field analysis with fabrication tolerances based upon input from manufacturing development. The mockups will be fixtured within a vacuum vessel and tested (to failure) for their insulation integrity at various levels of vacuum and helium gas concentrations. Room temperature helium gas will be used since it represents a worst case insulation breakdown scenario. Testing will establish vacuum and helium level concentration criteria under worst case conditions. The purpose of this testing is to verify that the designed insulation schemes can withstand peak quench voltages provided that the vacuum level and helium leakage rates are within established ranges.

3.11 EDDY CURRENT BREAKS

Eddy current breaks will consist of a metallic wedges coated with an insulating layer material. Development of the wedge and coating process will include process and material testing to ensure that the design is capable of meeting the voltage insulation requirements. The wedge will consist of either Incoloy 908 or 316 stainless steel coated with aluminum oxide, using a plasma spray process. This coating process must ensure a good bond between the wedge and the insulating coating. Samples produced for testing and will undergo thermal cycling to LN₂ temperatures and then undergo testing for coating adhesion. The coating will be tested for chipping, thickness, cracking, insulating properties, and wear. The samples will be produced during manufacturing process development and will be used for process and design qualification. In order to verify the wedge coating insulation integrity at cryogenic temperatures, dc hipot testing will also be performed at LN₂ temperatures.

Eddy current breaks will employ a bolted fastening system to secure the insulation and sections together. The method of attaching the bolts while maintaining the non-conducting path will be verified through mockups and tested with a dc hipot meter. The eddy current break configuration must sustain a 1 kV isolation between the octants with less than 1 mA of leakage current.

3.12 HELIUM ISOLATORS

Helium voltage isolators have undergone extensive component level testing and qualification throughout Phase I under direction from the TPX project (ref.: 1314-940417/JPI SERA-01). During production, the isolators will be purchased from a vendor in accordance with a written specification developed in conjunction with the TPX project with input from the magnet manufacturer. The performance specification will include: operating characteristics, insulation integrity, operating environments, thermal cycles, and structural loads due to cooldown / operation. The vendor will be required to certify all components supplied for installation in the TF magnet systems meet the specification requirements. Component level testing for the helium voltage isolators is described in section 3.16.

3.13 FLOW METERS

The helium flow meters for the TF magnet system are part of the TF quench detection system. The quench detection system components are selected and qualified by the TPX project, and purchased and integrated by the TF magnet manufacturer. Prior to purchasing the flow meters for installation, the TF magnet manufacturer will verify that the selected flow meters meet the specification requirements and have been properly qualified by the TPX project. The qualification requirement should include: the ability to work in vacuum, cryogenic temperatures, magnetic field, have sufficient sensitivity and resolution, sufficient dynamic range to withstand quench flow levels, and the ability to withstand surges and reverse flow. The testing will also qualify the flow meter design for the lifetime requirements including: thermal cycles, radiation, and mean time between failure. Once the product and vendor are qualified by the TPX project, the TF magnet manufacturer will review certifications and test data, and source inspect the vendor periodically to insure continued quality. Component level testing by the TF magnet manufacturer will be limited to room temperature operational verification and calibration.

3.14 FILTERS

The in-line helium filters will be purchased as standard items from a vendor specializing in this product. The vendor will be required to provide certification that the supplied components meet specification requirements covering: flow characteristics, pressure drops, vacuum characteristics, temperature range, and particulate clogging. No additional testing will be performed by the TF magnet manufacturer.

3.15 FITTINGS

The proposed pipe fittings to be used at the ends of the helium isolator / flow kit are standard, off the shelf items made by Cajon. Fittings on this type have been used previously in cryogenics applications with satisfactory results. Prior to finalizing the design and selection of the fittings, a requirements specification will be established. The TF magnet manufacturer will require that the vendor provide testing results and certifications that qualify the fittings for use in the TPX system. The requirements specification will include: maximum pressure levels, operating temperature range, flow rates, pressure drops, helium leak rates, structural loading characteristics (shear , compression, tension), and thermal cycle performance. No additional material and components testing will be performed by the TF magnet manufacturer prior to installation.

3.16 HELIUM ISOLATOR / FLOW KIT

The helium isolator / flow "kit" is comprised of the helium voltage isolator, in line helium flow meter, filter, and connections. It is assembled separately and supplied to the TPX project with the TF magnet assembly for installation at the TPX site. Every kit will undergo quality assurance testing and inspection prior to shipment. Once assembled the welds on the kit will be subjected to LN₂ cold shocking. After cold shocking, the welds will be inspected for cracks using die penetration techniques (see also section 3.2 and 3.3). Each kit will be tested for leaks using standard vacuum helium leak detection methods. Leak rates must be less than 3×10^{-9} atm-cm³/s. Each flow meter will be verified for operational performance and calibrated prior to shipment. The flow meter will be calibrated again prior to installation within the TPX system. Each kit will be pressure tested to insure that it withstands the pressure levels present at the inlet and outlet during quench. After the cold shock, leak, flow, and pressure testing are complete, each kit will undergo hipot testing to a level of 16 kV in order to verify its insulation integrity. Once testing is complete, the documentation will be included in the product data packet and the kit will be packed for shipment to the TPX site.

3.17 SPLICE JOINT HALVES

The coil to coil and coil to bus splice joints have been developed and tested by the TPX project during Phase I of the contract. The TF magnet assembly manufacturer will incorporate the existing design into its alignment and assembly process. In order to verify the magnet manufacturer's ability in producing quality splice joints, practice samples will be produced during manufacturing process development and sent to the TPX project for testing. In addition, the TF magnet manufacturer will investigate the benefit of non-destructive in-process quality control tests such as ultra-sonic inspection to verify percent solder bonding and test for flow obstruction that may have resulted in the fabrication process. Qualification testing on splice samples should include: operation at temperature & field, resistance across the joint, heat generation and flow characteristics, structural integrity and electrical and thermal cycling effects. The testing performed by the TPX project will be used to qualify the joint design and manufacturing process. Production level testing on the splice joints will be limited to: a) verification of process control parameters, b) dc electrical resistance at room temperature (gross error detection only), c) ultrasonic evaluation of percent solder bond, and d) gas flow verification.

3.18 VOLTAGE TAPS

In-process testing of internally terminated voltage taps contained within the CICC will be performed using two methods: a) standard four wire electrical resistance measurement and b) time domain reflectometry (TDR). The former technique will require little development effort. The latter technique is more complex and will be investigated in the context of materials and component testing. TDR equipment will initially be rented in order to verify the feasibility of this technique. This technique sends a source signal down the length of the wire and measures the time it takes the reflected signal to return. Using a time of flight analysis, one can determine the distance to the termination. This technique was used in a similar manner for superconducting strand inspection in support of the Superconducting Super Collider. However, the technique was used on straight lengths of conductor with open-ended terminations. It will be investigated if this technique is applicable in the curved geometry of the TF winding pack in addition to the present scheme of TPX voltage tap termination in which two un-insulated portions of the wire are joined together and shorted locally to the conductor cross section.

3.19 FIBER OPTICS

The design, qualification, and testing of the fiber optic quench detection system is the responsibility of the TPX project. It is the responsibility of the magnet manufacturer to provide in-process verification testing to insure the survivability of the fibers during manufacturing. As with the voltage taps, a simple in-process method for flaw detection within the co-wound fiber optic channels will be investigated. The proposed method uses a fiber optic test meter to determine distance to the mirror embedded in the fiber during cabling. These meters are standard in the telecommunications arena and are used to detect faults in fiber optic cable between signal repeaters. The meter would use optical time domain reflectometry (OTDR) to determine the time it takes for a light pulse to be emitted and reflected from the embedded mirror. The reflection time of the signal is directly related to distance from the mirror and index of refraction of the media. Any serious flaws within the fiber would reflect the signal back prior to reaching the embedded mirror and therefore indicate the location and possibly the magnitude (depending on the amount transmitted and reflected) of the fault. Qualification testing will be performed with fiber optic cable and mirrors would in a similar geometry to those used by the TPX project. In addition, the fibers will also be subjected to bends and crimping to determine the ability of the measurement system to locate and identify the location and severity of the fault.

Testing will also include manufacturing development of the fiber optic splice to verify that the process does not add unwanted optical interference to the system. This testing will be performed in conjunction with manufacturing process development models.

3.20 STRAIN GAGES

Strain gages will be mounted on the TF case at various high stress locations as designated by structural analysis. The purpose of these gages is to provide structural data during the operations of: cooldown, energization, quench, and plasma disruption. Currently gages are planned to be located on the: bolted joint faces, nose region, CS and PF magnet mounts, corners of the windows, etc. The strain gages must be able to work accurately in the temperature, magnetic fields, radiation, and high voltage levels of the Tokamak environment. Strain gages have been used successfully under similar conditions on magnets for the Superconducting Super Collider. Mockups will be constructed and cold tested in a magnetic field to verify the proposed operation when installed. The gages will consist of a measuring gage and a corresponding temperature and magnetic field compensating gage mounted to the TF case with a epoxy. The epoxy must withstand the temperature, radiation while maintaining a 1 kV voltage isolation between the case and gage.

3.21 FLOW IMPEDANCE TESTING

Flow through a conduit can be accurately correlated between largely different flowing conditions given equivalent Reynolds numbers. For the TF CICC at room temperature flowing conditions, pressures in excess of 6 MPa would be required to achieve an equivalent Reynolds number to that of the actual steady state flowing conditions. An alternative approach is to base the warm test flow on standard flow equations using empirical correlation of friction factors derived for CICC. The friction factor correlation used by E. Tada et al. gives good results for Reynolds numbers between 10^2 and 10^4 ; a range which is compatible with the actual flow conditions. The test fluid must have a sufficiently high density to viscosity ratio in order to attain the minimum Reynolds numbers given above. Excluding LN_2 cooled fluids due to cost considerations, the most appropriate choice of a testing fluid at room temperature conditions is gaseous argon. Testing will be performed to investigate the flow impedance sensitivity. This testing will use sections produced during winding machine trials and the dummy coil. Each will be subjected to various flow restrictions to determine the viability of the test. To be considered useful, the test must have enough sensitivity to distinguish between normal and abnormal flow conditions. Based upon initial calculations, argon gas with an inlet pressure of 11 atm and a flow rate of $1.71 \text{ std-cm}^3/\text{min}$ will be supplied to the CICC manifold. The estimated outlet pressure would be ~ 1 atm after traveling through a TF coil cooling path. Various pressures and flow rates will be investigated during the trials, along with multiple lengths and flow paths. Deliberate obstructions will be introduced in the system to determine the effect on the flow impedance readings. These tests will determine the viability of the test, as well as, establishing the test parameters and procedures used for production coils.

3.22 LEAK TESTING METHODS

Several methods have been proposed for leak detection in the CICC and the accompanying components which comprise the TF assembly. Different methods will be investigated for their: feasibility, practicality, and sensitivity. When possible, standard commercial methods and equipment will be employed. The extremely small pipe conductance of the CICC presents a difficult challenge to standard vacuum He leak detection. However, helium leak detection methods will be investigated on stub weld mock-up samples to verify if this technique is suitable. It is possible that the CICC pipe conductance is so small (thus the virtual leak is small) that evacuation on a local scale is still possible. Components or assemblies that are difficult to access or evacuate will use a pressure testing arrangement that employs one of two potential methods: a) an acoustic pickup that detects the sonic emissions of pressurized gas leaking through an orifice or b) a hand held wand which draws in air from and analyzes it for helium content. Commercially available standard He leaks will be used to calibrate and determine resolution of the latter two techniques. Parameters such as sensing distance, CICC gas pressure, and background interference will be optimized in order to obtain maximum sensitivity.

3.23 CENTRAL FORGING COOLING CHANNEL

The case cooling channel is comprised of a copper tube brazed to a stainless steel channel. Thermal contact between the two components must be maintained throughout the length of the cooling tube in order to insure good heat transfer. Testing will be performed on samples produced during manufacturing process development and will consist of cold shocking to LN₂ temperatures, thermal cycling and inspecting the bond between the two materials. Because of the complex geometry, UT or eddy current inspection most likely will not be effective. In-process testing will include: process control verification, visual inspection, die penetration, and destructive examination.

4. FUTURE WORK

Future work to formalize the completion and integration of the MCTP in the TF coil program will include the following: 1) establishment of pass/fail criteria for tests outlined in material and component test matrix, 2) periodic update of the MCTP to reflect modifications in design derived requirements, 3) integration with supplemental test plans, i.e. FMECA and Quality Assurance Plan, for a comprehensive TF testing approach, 4) completion of detailed test procedures, 5) determine facility and equipment requirements for testing, 6) develop test technician training requirements.

Appendix A

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Appendix Material and Component

Acceptance Test	Test Loc.	Rational for performing test	Phase of Production	Specificati /
1. Materials	Materials Testing Lab	<ul style="list-style-type: none"> • Provide base material data in accordance with design requirements and Structure and Cryogenic Design Criteria (SCDC) 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Tensile SCDC §I - • Strain SCDC §I - 4. • Strain - N Fatigue (• Cracks SCDC §I - • Cyclic loading
2. Welds	B&W and Material Testing Lab	<ul style="list-style-type: none"> • Verify welds meet structural requirements 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Tensile SCDC §I - • Strain SCDC §I - 4. • Strain - N Fatigue (• Cracks SCDC §I - • Cyclic loading
3. Helium Stub Welds	B&W	<ul style="list-style-type: none"> • Develop testing techniques 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Cable temperature • Full penetration • No cracks or voids
4. Case Mockups	B&W (Mt. Vernon)	<ul style="list-style-type: none"> • Develop weld and machining process to limit distortion 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Measure weld disto
5. Superconductor	TPX Proj.	<ul style="list-style-type: none"> • Qualify Superconductor and Vendor 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Qualify in accordan cable in conduit spe
6. Strain Limit	TPX Proj.	<ul style="list-style-type: none"> • Develop performance -vs.- strain plots 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Translation between • Flexibility of conduc
7. Conduit	B&W	<ul style="list-style-type: none"> • Develop crack detection method • Develop color chart for SAGBO 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Maximum allowable • SAGBO color chart
8. Coil Electrical Characteristics	B&W	<ul style="list-style-type: none"> • Change in cable resistance due to reaction • Inductance 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Support resistance i production coils
9. Coil Insulation	B&W	<ul style="list-style-type: none"> • Justify Tan δ • Develop detection methods 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Void / Resin Rich ar • Develop insulation t • Refine dc Hipot me • Develop in-process • Lifetime testing
10. Chimney Voltage Isolation	B&W	<ul style="list-style-type: none"> • Verify chimney region voltage isolation 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Determine voltage v vacuum levels, and
11. Eddy Current Breaks	B&W	<ul style="list-style-type: none"> • Insulation coating adhesion • Insulating technique for fasteners 	<ul style="list-style-type: none"> • Phase II 	<ul style="list-style-type: none"> • Eddy current break i • Insulation spray coa • Lifetime testing of cr

3 Test Matrix

Requirement & Source Requirement	Equipment Required	Equipment Sensitivity Required
1 /es SCDC §I - 4.2.2.5 3	<ul style="list-style-type: none"> • Cryogenic and mechanical material test facility 	<ul style="list-style-type: none"> • TBD
1 /es SCDC §I - 4.2.2.5 3	<ul style="list-style-type: none"> • Weld coupons • Cryogenic and mechanical material test facility 	<ul style="list-style-type: none"> • TBD
to exceed 400C	<ul style="list-style-type: none"> • Samples • Temperature sensitive weld coating • Die penetration • UT system 	<ul style="list-style-type: none"> • TBD
n	<ul style="list-style-type: none"> • Large scale 3 dimensional coordinate measurement system 	<ul style="list-style-type: none"> • TBD
with superconducting cable and cations	<ul style="list-style-type: none"> • Superconducting cable test facility 	<ul style="list-style-type: none"> • TBD
rand strain and conduit strain during manufacturing	<ul style="list-style-type: none"> • Superconducting cable test facility 	<ul style="list-style-type: none"> • TBD
ack size = TBD	<ul style="list-style-type: none"> • Eddy current system • Pressure system • Reacted samples in various O₂ levels 	<ul style="list-style-type: none"> • TBD
inductance measurements of	<ul style="list-style-type: none"> • CICC samples • Reaction oven • Volt Meter • Current supply • LCR Meter 	<ul style="list-style-type: none"> • TBD
not to exceed TBD kness / coil location measurement ement voltage limits hole detection technique	<ul style="list-style-type: none"> • Insulated manufacturing mockups, dummy coil • DC Hipot • Eddy current system • Impulse measurement system • Induced voltage system • Tan δ system (rent / lease) 	<ul style="list-style-type: none"> • TBD
stand levels for various geometry's, ium concentrations	<ul style="list-style-type: none"> • DC Hipot • vacuum vessel • mockups 	<ul style="list-style-type: none"> • TBD
st maintain 1 kV @ 1mA must firmly adhere to substrate ng	<ul style="list-style-type: none"> • Plasma coated samples for adhesion testing • Hipot 	<ul style="list-style-type: none"> • TBD

TPX TF Material and Component Test Plan

Acceptance Test	Test Loc.	Rational for performing test	Phase of Production	Specificati / 7
12. Helium Isolators	TPX Proj.	• Qualify Helium Isolators and vendor	• Phase II	• Helium Isolator mu requirements.
13. Flow Meters	TPX Proj.	• Qualify Flow Meters and vendor	• Phase II	• Flow Meter must m requirements.
14. Filters	Vendor	• Filter meets requirements	• Phase II	• Helium Filters must
15. Fittings	Vendor	• Fittings meet requirements	• Phase II	• Cajon fittings must
16. Helium Isolator / Flow Kit	B&W	• Kit tested and ready for installation in Tokamak	• Phase II	• Leak check all wel • Pressure check ass • Flow check for flow • Hipot check of isol
17. Splice Joint Halves	B&W and TPX Proj.	• Qualify splice joint and manufacturing process	• Phase II	• Solder bond betwe • Cooling channel flo • Cold test qualificati
18. Voltage Taps	B&W	• Develop testing techniques	• Phase II	• Investigate TDR m. • Investigate sensitiv
19. Fiber Optics	B&W	• Develop testing techniques	• Phase II	• Investigate equipm
20. Strain Gages	B&W and Magnetic cold test lab	• Qualify strain gage selection and mounting	• Phase II	• Test strain gage for voltage isolation field dependence thermal cycles
21. Flow Impedance Testing	B&W	• Develop testing technique	• Phase II	• Develop testing tec to simulate cold hel
22. Leak Testing	B&W	• Determine sensitivities of measurement instrumentation	• Phase II	• Sonic detection me • "Sniffer" wand metl
23. Central Forging Cooling Channel	B&W	• Proof of process tests	• Phase II	• Solid braze bond br

Requirement & Source t Requirement	Equipment Required	Equipment Sensitivity Required
meet all performance and structural	• TPX project testing lab.	• TBD
all performance and structural	• TPX project testing lab.	• TBD
et all performance requirements	• Vendor testing	• TBD
et all performance requirements	• Vendor testing	• TBD
bly ter response	• Vacuum Helium Leak test system • Pressure testing system • Flow meter display device • Hipot	• TBD
conductor and joint restrictions	• UT system • Flow / pressure measurement system • TPX Project cold test facility	• TBD
urement of 4 wire resistance measurement	• TDR meter (rent / lease) • Current supply • Volt meter • Samples of CICC w/ instrumentation	• TBD
for Optical TDR measurement	• Optical TDR equipment (rent / lease) • Samples of fiber w/ mirrors	• TBD
	• Strain gage samples and mounting mockups • Magnetic cold test facility • Hipot • Digital multimeter	• TBD
que using argon flow through CICC n flow during operation.	• Argon supply • Flow meters • Pressure gages • CICC samples (manufacturing trials and dummy coil)	• TBD
d	• Standard Vacuum Helium Leak Detector • Pressure system • Sonic detection system • Wand detection system • Samples	• TBD
een copper tube and stainless steel	• Manufacturing samples • Die Penetration • Saw and Polisher for destructive examination	• TBD

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT
AND MANUFACTURE

Contract B235308

SDRL 37(A)
Toroidal Field Magnet
Reaction Development Program

13-950811-BW-WYoung-12

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**Babcock & Wilcox
Record of Revision**

Rev. No.	Date of Issue	Sect./Par.	Description/Authorization
N/R	18-Aug 95		Initial Release -

MANAGEMENT SUMMARY

B&W has developed a finite element computer model of the heat transfer within the TF coil cross section. This model has been correlated with experimentation to adjust for changes in the thermal conductivity of the dimensional spacers and for the augmentation of heat transfer by utilizing a partial pressure atmosphere during the reaction cycle. This model can be transformed for use on the PF1 to 5 coils also. Its validity for that application should be checked with experimentation when suitable conductor becomes available.

This computer model can be used to evaluate the feasibility of a superconducting strand reaction cycle when a specific thermal profile is proposed which includes manufacturing tolerances. Alternately the model could be used to propose working tolerances, particularly of span times, when a nominal thermal reaction profile is identified.

Certain design alternatives of the TF coil assembly call for a high strength bond between the vacuum impregnation resin and the surface of the conduit. This would permit the coil assembly to respond to thermal or mechanical loads monolithically with great strength and rigidity. B&W has conducted testing to evaluate the shear strength of the bond between the vacuum impregnation resin and the conduit surface after several alternate cleaning operations. The testing has identified several reasonable cleaning techniques based on mechanical abrasion which result in a high strength bond at both room temperature and at cryogenic temperature.

During the winding of the coils, either TF or PF, it is necessary to insert a spacer in the zone which ultimately will be occupied by the insulation. This spacer is intended to maintain the dimensional precision of the coil during the superconductor forming thermal reaction cycle. Because of the extended thermal exposure, the scouring effects of the vacuum atmosphere and the mechanical pressures inevitable in the reaction process, there is a risk of diffusion bonding between the dimensional spacer and the conduit of the coil. Diffusion bonding of the spacer would interfere with removal of the spacer and, if severe, could compromise the functionality of the conduit.

B&W has conducted diffusion bond testing of several candidate spacer materials and has identified the bonding risk for those materials in the bare metal state. B&W has also tested a proposed diffusion barrier, boron nitride, which consistently proved satisfactory in preventing bonding between the spacer and the conduit surface.

2

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1.0 SCOPE:

This document presents the results of the Reaction Development and Conduit Cleaning program. The test plan for this program was submitted as SDRL 37(A) dated October 5, 1994. The testing executed is in support of the reaction heat treatment cycle for the Nb₃Sn conductor used in both the TF and CS coils.

The testing executed is briefly listed here and discussed in detail below:

Table 1. SDRL 37 (A) Testing

Reaction Development and Conduit Cleaning Tests	
Test	Description
Heat Transfer Models	Computer model of TF coil cross section is generated. Using experimental data, the model is calibrated and empirical coefficients generated for use in TF and PF reaction simulations. (Original plan par. 2.1.)
Coil Matrix Test Block	Full scale segment of TF coil is used to generate heat transfer coefficients for use in computer models. (Original plan par. 2.3.)
Cleanliness and Bonding Experiment	Evaluate post reaction cleaning methods on VPI bond strength. (Original plan par. 2.4.)
Reaction Distortion Experiment	Evaluate thermally induced distortion during the reaction cycle. (Original plan par. 2.5.) This testing is reported in SDRL 37(B), Bending and Forming Development
Reaction Cycle Bonding Experiment	Evaluate spacer tooling materials for the reaction cycle. (Original plan par. 2.6.)

2.0 HEAT TRANSFER MODELS.

2.1 Objective:

The objective of this analytical portion of the development plan is to create models which can be used to simulate the heat up and cool down characteristics to be encountered by the TF and CS coils during the reaction cycle.

A preliminary model aimed at predicting the time response of a TF magnet winding to various proposed reaction cycles is described below. Of particular interest is the temperature differential between the interior and exterior of the winding pack. Minimization of the worst case temperature differential (through reaction winding pack design) will insure that all of the Nb_3Sn in the winding will react properly during the proposed curing cycles. Also of interest is the time response of the winding through the temperature interval where the Incoloy 908 conduit is most susceptible to the SAGBO (Stress Accelerated Grain Boundary Oxidation) phenomena. The SAGBO sensitization range will be reached before the high temperature set point is reached. The winding pack temperatures should transition through this interval rather quickly in order to reduce the risk of SAGBO. Additionally, the model can be used to develop heat input requirements to obtain a given $T(t)$ profile in the winding pack. Such information is desired as an aid to developing a specification for the reaction furnace.

2.2 Model Description

A two dimensional ANSYS finite element model is used for analysis. The model represents a perpendicular cross section to the winding of a TPX toroidal field (TF) magnet away from the transition regions, and conforms to the geometry of drawing E-1335000-P0. During the reaction process, the areas of insulation, as shown in drawing E-1335000-P0, are actually occupied by metallic spacer material. These spacers are removed after the reaction, and the insulation system is then installed. This model includes these spacers, both turn-to-turn, and layer-to-layer.

The geometry of the model is chosen to simplify the analysis process, reduce the computation time and permit rapid assessments of temperature profiles and/or spacer geometry's. The TF magnet winding is a seven turn by twelve layer array. Midline coil symmetry allows reduction of the computational winding pack array to three and one-half turns by six layers. Intuitively, the elements in the center of the winding, layers 6 and 7 and turns 3 and 4, will respond the slowest to heat applied to the outside of the winding pack. In this case, it is assumed that the innermost layers, 6 and 7, are sufficiently far from the sides of the winding pack (layers 1 and 12) that heat flow across all the layers to reach layers 6 and 7 can be neglected. This is particularly true for layer spacers of a high conductance material. These additional assumptions allow further symmetry reduction to a model that consists of three and one-half turns by one-half layer.

The model is meshed with eight-noded plain strain quadrilateral elements. (These elements simulate most closely the cross section of an infinite rod). This element selection is optimal for minimal heat transfer out of the plane of the element when compared with heat transfer along the element. This type of element is used in all areas of solid material, i.e. the spacers and the CICC.

The reaction modeling must also include the heat transfer relationship between bodies that are in contact with one another. Though the winding will be clamped during the reaction cycle, the contact between spacers and the CICC is non-intimate, varies from point to point, and can be expected to vary with temperature as well. Hence the contact resistance to heat transfer at these interfaces is very difficult to predict. Not only is there difficulty in prediction, but there would also be inconsistency in achieving the modeled contact state during experimentation. The interface between two contacting surfaces is therefore modeled with radiant heat transfer as a limiting worst case contact. This heat transfer mechanism should be limiting because radiant heat transfer between bodies in a vacuum is less effective than any conduction. The radiation case should therefore be the limiting conservative case. The radiation is modeled by the use of radiation links. These radiation links connect the midside nodes on the sides of elements that are in contact with the elements of other bodies. The model is fully presented in SDRL 29.

The radiation links we use are for gray body radiation, and thus are susceptible to assumptions made about surface emissivities. The surface emissivities used for reaction model materials are given in Table 2. It is important to note that heat transfer between two parallel planar surfaces is defined as:

$$Q = \frac{e_1 e_2 \sigma_B}{[e_2 + (1 - e_2) e_1]} [T_2^4 - T_1^4]$$

where e_1 and e_2 are the emissivities of the respective surfaces and σ_B is the Stefan-Boltzmann constant. As previously mentioned, even with high surface emissivities, heat transfer by radiation should be much less efficient than heat transfer by any conduction (contact resistance included) and should thus provide a conservative estimate of the heat transfer rate to the interior of the TF winding pack. To fully bound the calculations and to provide an upper limit on the heat transfer rate, an analysis was also conducted assuming intimate contact, with no contact resistance, between spacer and CICC bodies.

Symmetry has reduced the TF winding pack heat transfer problem down to that approaching a one dimensional heat transfer problem. There is only one free edge, representing the outside surface of the winding, across which there can be a heat transfer. All other boundaries are constrained by the symmetry condition of no heat transfer across itself. Within the winding, however, more than a simple one dimensional heat transfer is seen. Within the winding there is a radiation/reradiation interaction between the CICC elements and the spacer elements. This interplay results in a two dimensional transfer within the winding itself. The 'driving' heat transfer, because of its one dimensional nature, is handled quite easily by nodes in space. These nodes are connected to the elements representing the surface of the winding with radiation links. The "master" nodes are then forced to follow a temperature profile. The mechanism of the heat transfer is the gray body radiation of these master nodes to the nodes on the surface of the winding to which they are linked. The master nodes are allowed to behave as infinite heat sources, and as such have no limitation, other than that intrinsic to the radiation link, to the amount of energy they output.

One other simplification of significance was made. This simplification is in the modeling of the interaction of the strands of conductor with the conduit themselves. This region shows not only contact resistance to heat transfer between the conductor to the strands, but also between the strands themselves. The model is intended as a first-order estimate. As such, the analysis is intended to predict the response of the overall system, and not necessarily the response of discrete components of the system. True to this line of reasoning, the complex interplay between the conduit and strands of conductor are not individually modeled, but are combined into "smeared" CICC properties. These smeared properties provide a good overall estimate of the behavior of a section of the CICC, matching the thermal capacity and effective conduction through the section. Although this assumption forces the predicted temperature distribution through the section to be inaccurate, the total energy deposition and time constant will be matched, providing for accurate predictions of response time and energy input requirements for reaching equilibrium. The smeared CICC thermal properties are listed in Table 1, along with the other thermal properties used.

Table 2: Material Properties Used for Thermal Modeling							
			200 K	400 K	600 K	800 K	1000 K
Copper							
	ρ	(kg/m ³)	8933				
	Cp	(J/kg•K)	356	397	417	433	451
	k	(W/m•K)	413	393	379	366	352
	e		.57				
Incoloy X-750 (Chemically similar to Incoloy 908)							
	ρ	(kg/m ³)	8510				
	Cp	(J/kg•K)	372	473	510	546	626
	k	(W/m•K)	10.3	13.5	17	20.5	24
	e		.30				
Stainless Steel (316)							
	ρ	(kg/m ³)	8238				
	Cp	(J/kg•K)	432	504	550	576	602
	k	(W/m•K)	11.6	15.2	18.3	21.3	24.2
	e		.24				
CICC Smear							
	ρ	(kg/m ³)	6372				
	Cp	(J/kg•K)	375				
	k	(W/m•K)	4				

2.3 TF Heat Treatment Mockup Studies

In order for a firm foundation in reality to be established, the predictions of the analyses model need to be calibrated with actual test data. The model was therefore subjected to a time-temperature profile to which a mockup test sample was exposed. The configuration of these two items was also the same, with the use of copper, with overhanging tabs, as the spacer material in a vacuum environment. Also calibrated was the increase in response time at lower temperatures where argon can be used to quicken the process (Commercially available argon is not sufficiently oxygen-free to use at temperatures where SAGBO is of concern). The general trend of the response of both the test article and the analysis model were similar, but the test article showed a slower response than was predicted.

To correlate the data, the behavior of the innermost conductor (turn 4, layer 6) of the test piece at each of the hold temperatures was examined. The predictions of the model for this same conductor were compared at these hold temperatures. The delay between leveling off the oven at the hold temperature, and the time for the innermost conductor of the test piece to reach within 5°C and 2°C of this temperature were compared with the delay times suggested by the model. In each case, at each temperature, the response of the test piece was 2.51 times longer than that predicted by the model. This result suggested that the analysis model accurately predicted the heat capacity of the winding, and the energy deposition into the winding, but was less precise in predicted the rate at which energy enters into the winding pack. This rate is controlled by the modeling of the relation between the oven and the surface of the winding pack. Because of the constant factor, the rate at which energy crossed this boundary was too high. To adjust for this, the emissivity at the outside surface of the winding pack in the model was divided by the 2.51 factor. Since gray body radiation scales linearly with both the emissivity and the view factor, the variable adjustment in the model has the meaning in real terms of adjusting the product of the view factor and the emissivity. This calibrated model was then subjected to the same reaction profile.

The correlation between the calibrated model and the reaction mockup is actually quite good and is summarized in the figure 1. This figure shows the predicted values of temperature of the outermost conduit wall, and the innermost conductor, and the data values obtained for these same points in the mockup test piece. The predicted values fall near the average of the values of the test piece. This is as one would expect due to the smearing of the CICC. It is important to note that the deviation is greatest at the beginning of each temperature ramp, and that as the target temperature is approached and held, the deviation decreases. The temperature deviation is very small within 15 hrs of reaching equilibrium. The error is decreased at elevated temperatures, and is under 3% except in the very early stages of approaching the first temperature hold.

Figure 1. TF Heat Transfer Model Response

2.4 Conclusions.

The model provides useful self-consistent comparisons of reaction configurations. These predictions are good for relative comparisons between configurations. These predictions are also good for order-of-magnitude response times.

The use of spacers, during the reaction process, made of material with a high thermal conductivity is desirable for a more uniform and rapid heat up of TPX coil winding. The current baseline is to use spacers made of Incoloy 908, a poor thermal conductor. Any material which shows better conductive characteristics than Incoloy 908 should decrease the time required for the reaction process. The other steel used, a stainless steel, shows nearly the same response as with the Incoloy. The spacer material needs to be high quality oxygen free material in order not to increase the probability of SAGBO.

There was an indication in the preliminary modeling that using a "tabbed" spacer design is conducive to improving heat transfer into the winding pack. In this concept extensions are provided on the spacers that are then bent over the outermost surface(s) of the winding pack. This allows the heat energy from the oven to be intercepted by these spacers and transmitted into the winding pack through a solid conduction body. This concept is particularly effective when combined with using a material with high thermal conductivity. A conservative analysis with the tabbed design, allowing only radiation between spacer elements and CICC elements, is seen to be more efficient than the upper bound of the non-tabbed design which allows intimate contact (no contact resistance) between CICC and spacer elements.

The model shows a good response to all of the prototype reaction profiles. The model predicts that the lag time between leveling the oven at the reaction temperature and the winding reaching an equilibrium is a small portion of the hold time at the reaction temperature. Also the model predicts, in all three reaction profiles, a fairly fast passage through the temperature interval of greatest SAGBO concern.

A calibration to mockup data has been made. This calibration provides for a fairly accurate prediction of response time of the winding pack. The calibration was only necessary in the modeling of the heat transfer between the oven and the winding pack, suggesting a good model prediction of the heat capacity and energy deposition into the winding pack, as well as reasonable estimations of the heat transfer within the winding pack.

An extremely accurate prediction of the temperature distribution across the winding pack could not be obtained with this model, due to smearing of the properties of the conductor and conduit. The correlation to mockup data has shown, however, that the temperature distribution predicted is a good estimate of the average temperature of each turn of conductor.

The calibrated model shows a good correlation to predicting the response time of the innermost conductor, meaning that current modeling has matched the heat capacity of the winding pack, the energy deposition rate, and the overall energy deposition. This information is useful in establishing a specification for the reaction oven.

Continuing efforts are focused on correlating with data for the reaction mockup with different materials and configurations. Included are materials changes from copper to stainless steel as spacer materials, and the elimination of tabs on the copper spacers. Additional effort is being placed in establishing a more accurate prediction of temperature distribution. This will be achieved by separating the conduit material from the conductor material. Additionally, interest has been expressed in a more accurate temperature prediction in one quarter of the winding pack, rather than through only one section.

3.0 COIL MATRIX TEST BLOCK.

3.1 Objective: The computer heat transfer models described above initially incorporated certain assumptions for physical characteristics of the materials. These assumptions include emissivity and thermal contact resistances. The objective of this experimental portion of the development plan is to support the heat transfer model development. By the use of actual data, coefficients can be developed to refine the initial model assumptions.

3.2 Material and Methods:

Dummy TF conductor (Incoloy-908 conduit of the TF configuration with a 360 strand copper cable simulating the superconductor. The cable was wrapped with stainless steel foil in a prototypical manner) was received and sectioned into 84 pieces of approximately 19 inch length.

Electrolytic copper sheet 0.076" thick was used to maintain the spacing for the insulation gap on the TF coil section fabricated. The turn to turn spacers were 0.875" wide by the full length of the mockup whereas the pancake to pancake spacers were segmented at 2.25". The segmented top most and bottom most copper spacer layers were tack welded together for structural integrity. All spacers were notched as necessary to accommodate the instrumentation thermocouples and tooling clamps. Figures 2 and 3 are cross sections of the heat transfer mockup and show the placement of the copper spacers. The first configuration tested was with copper tabs intended to enhance heat transfer. The second configuration was again fabricated of copper but without the heat transfer tabs.

Stainless steel grade 304 sheet 0.072" thick was used to maintain the spacing for the insulation gap on the third configuration. The placement was the same as for the second configuration except for replacing all the copper spacers with stainless steel spacers.

Boron nitride aerosol spray (Carborundum Corp., "Combat" brand) was used as a diffusion barrier on both the copper and stainless steel spacers to prevent sticking. The coating was white when initially sprayed but changed to a gray color after the heat treatment.

The matrix was mounted in a tooling fixture (see figure 4) for support and insulation on the ends. The end insulation of the fixture consisted of several layers of stainless steel sheet to shield radiant heating and 1" of ceramic fiber insulation board (Babcock & Wilcox 'Kaowool 2300 M-Board') over each end to enhance insulation during the argon partial pressure testing. This insulation can be seen in the photograph, figures 5 and 6.

Twenty four type K thermocouples were mounted on the heat transfer mockup and recorded at 2 minute intervals during the thermal cycles. Figure 7 illustrates the thermocouple placement during the initial mock up runs with copper spacers with heat transfer tabs. Figure 8 illustrates a slightly revised placement used for the second and third configurations of the mockup. Figure 9 shows a close-up of the installation of the thermocouples.

The mockup and its associated tooling and instrumentation was installed in a 19" diameter vacuum retort which was modified to also permit operation with a partial pressure of argon. Figure 10 shows the mockup staged for insertion or removal from the retort. The retort was externally heated by a removable four zone clamshell furnace. Temperature ramps were manually performed with setpoint adjustments at 15 or 30 minute intervals. Temperature control thermocouples were in contact with the external surface of the retort.

Cross Section of TF Heat Transfer Mockup
Copper Spacers with Heat Transfer Tabs

Figure 2. Heat Transfer Mockup w/ Tabbed Copper Spacers

Cross Section of TF Heat Transfer Mockup
Showing Copper and Stainless Steel Spacers
Without Heat Transfer Tabs

Figure 3. Heat Transfer Mockup w/ Straight Spacers

Figure 4. Heat Transfer Mockup Tooling

Figure 5. In Process Heat Transfer Mockup Assembly

Figure 6. Close Up of Mockup Assembly

Notes:
1. Thermocouple 23 was mounted to a copper spacer rather than in a conductor.
2. Thermocouples not shown on Longitudinal map were mounted on centerline.

Figure 7. Thermocouple Positioning - First Configuration

Q

●15

●12

●16

●17

●13

●18

●21

●8

●20

●19

4●

●5

Bottom

Top

Notes:

1. Thermocouples not shown on Longitudinal map were mounted on centerline.

Figure 8. Thermocouple Positioning - Second Configuration

●22	●21	●8	●20	●19	
●17	●16	●12	●15	●14	●11
4●		●5			

Bottom

Figure 9. Close Up of Thermocouple Set Up

Figure 10. Heat Transfer Mockup in Staging Position

3.3. Results:

The following runs were executed:

Table 3

Heat Transfer Mockup Runs				
No.	Configuration	Thermal cycle	Atm	Comments
1 (MD)	Cu spacers w/ tabs	Bakeout	Vacuum	Insulation outgassing
14 (DL)	Cu spacers w/ tabs	Slow heat	Vacuum	Stopped to check TC insertion
15 (DL)	Cu spacers w/ tabs	Slow heat	Vacuum	
17 (DL)	Cu spacers w/ tabs	Fast heat - stepped	Vacuum	Data logger interrupted
20 (DL)	Cu spacers w/ tabs	Fast heat - stepped	1 Torr Ar	to 340C only
21 (DL)	Cu spacers w/ tabs	Fast heat	Vacuum	from 340C only
22 (DL)	Cu spacers w/ tabs	Fast heat-stepped	Vacuum	
25 (DL)	Cu spacers w/o tabs	Fast heat-stepped	Vacuum	
30 (DL)	SS spacers w/o tabs	Fast heat	Vacuum	to 185C only
34 (DL)	SS spacers w/o tabs	Fast heat	Vacuum	340C to 650C only

MD = Manually collected thermocouple data

DL = Data logger data

When the mockup assembly was disassembled after run 22, the lengths of conduit were examined. All of the pieces appeared sound and free from cracking or non-adherent film. The surface of the pieces were discolored, particularly those pieces which were on the interior of the mockup. This discoloration is shown in figure 19. The conduit lengths appeared unchanged during the rebuild following run 25.

In examining the run summary graphs, it should be noted that the plotted center mockup temperatures are not strictly consistent between the first build of the mockup (runs up through 22) and subsequent builds because of the revision of the thermocouple locations.

The data logger program was modified between run 25 and run 30 to improve real time surveillance of the furnace run. This change also modified the damping of the recorded data (recorded data points were changed to 30 second samples every two minutes rather than a two minute sample every two minutes). This change in the data recording can be observed as an increased amplitude in the variability of the furnace temperature.

A temperature excursion of the furnace can be observed on the 185°C hold of run 25. The source of this is uncertain but is believed to be a misinterpretation of engineering instructions by operating personnel.

During run 34, a heat interrupt occurred during the ramp to 340°C; this can be seen on the plot. The heat up curves for this portion of the run should therefore be ignored.

3.4 Conclusions:

Boron nitride functioned satisfactorily as a diffusion barrier in these experiments. It was not durable however. If boron nitride is used as a diffusion barrier for subsequent tooling spacers, it should be applied by a technique which would provide greater durability such as flame or plasma spray.

For a discussion of the findings from these data see the section on analysis of the heat transfer experiment. This can be found in section 2 of this document.

Figure 11. Heat Transfer Mockup Run No. 15

Figure 12. Heat Transfer Mockup Run No. 17

Figure 13. Heat Transfer Mockup Run No. 20

Figure 14. Heat Transfer Mockup Run No. 21

Figure 15. Heat Transfer Mockup Run No. 22

Figure 16. Heat Transfer Mockup Run No. 25

Figure 17. Heat Transfer Mockup Run No. 30

Figure 18. Heat Transfer Mockup Run No. 34

Figure 19. Conduit Discoloration after Initial Heat Transfer Runs

4.0 REACTION CYCLE BONDING EXPERIMENT

4.1 Objective: During the reaction process there is a need for a spacer to be inserted between the individual layers and between the pancakes of the coils to maintain dimensional accuracy. The objective of this experimental program was to evaluate the tendency to diffusion bond and thus stick for various candidate spacer material and to test the effectiveness of a selected diffusion barrier.

4.2 Materials and methods:

Incoloy-908 coupons were taken from GFM dummy TF conduit. The empty conduit had been moderately cold work from conduit fabrication and had not been age hardened. Square coupons 7/16" with rounded corners were laser cut from the conduit for testing. They were cleaned prior to assembly by an alcohol wipe.

The following candidate spacer materials were tested. All were wiped with alcohol prior to assembly.

- Half hard electrolytic copper (Hand polished with a non-metallic abrasive pad, Norton ultra fine "Bear-Tex", prior to assembly in addition to the alcohol wipe.)

- Stainless steel (Cold rolled 302)

- Mild steel

- Incoloy-908

Boron nitride aerosol spray (Carborundum Corp., "Combat" brand) was used as a diffusion barrier on a portion of each of the candidate spacer materials. The coating was applied with a light coat at room temperature after an alcohol wipe. No further treatment was applied prior to assembly to the test fixture. The coating was white when initially sprayed but changed to a gray color after the heat treatment.

Additional electrolytic copper spacers were used in the test assembly for stability of the setup.

A test fixture was fabricated which provided simultaneous dead loads of both 8.1 and 16.2 psi. After the unit was assembled, it was installed in a vacuum furnace and subjected to 200 hours at 650°C to simulate a typical reaction cycle. Ramping up and down to the test temperature was approximately 25°C per hour.

Figures 20 through 24 are a series of in process photographs which demonstrate the process used in the experiment.

4.3 Results:

After the thermal cycle, the bond strength of selected samples was tested in shear at room temperature for the various interfaces. The results are tabulated in Table 4. The capacity of the testing equipment was 130psi shear load; therefore, an entry of '>130' indicates that the interface was tested to the machine capacity and did not fail.

Figure 20. Reaction Bonding Test Stack Being Assembled

Figure 21. Completed Test Assembly with Dead Weight Installed

Figure 22. Additional Test Coupons have been Added to the Test Assembly

Figure 23. End View of Test Stack Prior to Furnace Loading

Figure 24. Test Stack Installed in Furnace with Instrumentation.

Table 4

Coupon Shear Strength		
Interface Evaluated	Shear strength in psi (8.1 psi dead load)	Shear strength in psi (16.2 psi dead load)
Copper - Stainless Steel	Stuck (6 x)	Stuck (3 x)
Copper - Coated Stainless Steel	0 (2 x) Very Slight 0.16 (2 x)	Very Slight 0.17 4.3
Stainless Steel - Incoloy 908	0 (2 x) >2.9 <5 >130 Stuck (2 x)	0 (3 x)
Coated Stainless Steel - Incoloy 908	0 (6 x)	0 (3 x)
Copper - Incoloy 908	113 >130 (15 x) Stuck (12 x)	>130 (8 x) Stuck (6 x)
Stainless - Stainless -	Stuck (2 x)	Stuck
Coated Stainless - Coated Stainless	Very Slight (2 x)	Very Slight
Coated Stainless - Copper	Very Slight (2 x)	Very Slight
Steel - Incoloy 908	Very Slight (2 x) >8.4 <10.5 Stuck	0 Stuck
Coated Steel - Incoloy 908	0 (4 x)	0 (2 x)
Copper - Copper	>130 (2x) Stuck (2 x)	>130 Stuck
Incoloy 908 - Incoloy 908	Stuck (2 x)	0
Coated Incoloy 908 - Coated Incoloy 908	0 Stuck	0
Copper - Coated Incoloy 908	0 Stuck	0

4.4 Conclusions

All candidate tooling material (copper, stainless steel, Incoloy-908 and mild steel) selected for testing are at risk for sticking to Incoloy-908 if used in a bare metal to bare metal condition. Each of the candidate materials should be acceptable if coated with boron nitride prior to assembly. It is particularly important, if copper is used, that the coating be inspected for integrity prior to assembly.

The method of coating the spacers with boron nitride used in this experiment results in a satisfactory coating but is not adherent. If boron nitride is to be used as a diffusion barrier, an alternate method of coating (such as flame or plasma spray) should be investigated.

After completion of the furnace run, some discoloration was observed on the surface of some of the test specimens. This discoloration apparently was associated with outgassing from the copper spacers used in the test stack. If copper tooling spacers are used in production, they ought to be outgassed prior to production use to minimize such a phenomenon in production.

5.0 CLEANLINESS AND BONDING EXPERIMENT

5.1 Objective:

One alternative design for the TPX magnet coils calls for the Vacuum/Pressure Impregnation resin to bond to the surface of the conductor conduit at a high level of integrity. The resulting composite coil assembly would then resist local deformation and movement with great stiffness and strength. This concept requires a high and predictable bond strength between the resin and the surface of the conduit.

The objective of this experiment is to develop a cleaning technique which facilitates such a bond. The intent is that such a cleaning technique would be used after the reaction process and prior to coil assembly with insulation.

5.2 Materials and methods:

The experiment was conducted in three stages:

- 1) A sampling of mechanical cleaning techniques was performed to select samples of cleaning equipment for further evaluation. This initial survey was performed on available stainless steel conduit and evaluated visually.
- 2) Several selected cleaning techniques were executed on Incoloy 908 coupons and assembled into VPI bonded test buttons. These were then tested at room temperature to determine shear strength under compressive load.
- 3) Based on the results of the second stage, a subset of the cleaning techniques was further evaluated using the same test technique at both room temperature and at 77°K.

5.3 Initial Survey Results:

The initial survey of mechanical cleaning techniques was conducted on 304 stainless steel 1" square conduit. The results of that survey are tabulated in table 5. The techniques marked with an asterisk were chosen to be further evaluated in the cleaning survey in the second stage as suitable representatives of mechanical cleaning. The basis for the selection include visual uniformity, degree of exposure of fresh metal and the appearance of some surface disturbance to aid in bonding.

Table 5

Mechanical Cleaning Survey			
Run #	Media	Technique	Evaluation
Al₂O₃ Flap Wheels			
1*	120 Grit (McMaster-Carr 4653A626)	13 passes at 1200rpm	Very slight longitudinal bright scratches
2	80 Grit (McMaster-Carr 4563A618)	5 passes at 1200 rpm	Slight longitudinal bright scratches
3	60 Grit (McMaster-Carr 4653A611)	5 passes at 1200 rpm	Slight longitudinal bright scratches
Nylon Brush Wheel			
4	.006" Filament (McMaster Carr 4747A62)	5 passes at 1200 rpm	Surface brightened; no textural change
Si/C Nylon Filament Wheel			
5	120 Grit (McMaster-Carr 4901A11)	5 passes at 1200 rpm	Slight longitudinal bright scratches. Not as uniform as 1-3
6*	80 Grit (McMaster-Carr 4901A11)	5 passes at 1200 rpm	Slight longitudinal bright scratches. Not as uniform as 1-3
ScotchBrite Abrasive Pad			
7	Type A Very Fine	25 strokes by hand	No change observed
Al₂O₃ Wheels			
8	Very Fine Buff Blend (Std Abrasive 880316)	5 passes at 1200 rpm	Very slight longitudinal bright scratches
9*	Medium Buff Blend (Std Abrasive 880316)	5 passes at 1200 rpm	Very slight longitudinal bright scratches
10	Unitized Very Fine (Std Abrasive 824105)	5 passes at 1200 rpm	Non uniform longitudinal polish. Possible smearing.
11	Unitized Fine (Std Abrasive 833105)	5 passes at 1200 rpm	Non uniform longitudinal polish. Possible smearing.

* These techniques were chosen to be further evaluated in the cleaning survey as representative of mechanical cleaning.

5.4 Stage 2 Experimentation Results: Initial testing of compression/shear samples:

Sample preparation:

Incoloy-908 coupons were taken from GFM dummy TF conduit.

The empty conduit had been moderately cold work from conduit fabrication and had not been age hardened.

Square coupons 7/16" were laser cut from the conduit for testing. Figure 26 shows the coupon configuration.

They were cleaned prior to heat treating by an alcohol wipe. Test coupons were heat treated for 200 hours at 650°C in a vacuum furnace with heat-up and cooldown ramps of 25°C/hour to simulate the reaction process.

Coupons were cleaned after reaction processing in the following manner:

1. Control specimen. Alcohol wipe only.
2. Chemical etch in HCl
3. CO₂ 2 blast
4. Al₂O₃ blast (220 Grit) and CO₂ blast
5. Scotchbrite and Alcohol wipe
6. Mechanical clean method #1 and air blow off
7. Mechanical clean method #1 and CO₂ blast
8. Mechanical clean method #6 and air blow off
9. Mechanical clean method #6 and CO₂ blast
10. Mechanical clean method #9 and air blow off
11. Mechanical clean method #9 and CO₂ blast

The CO₂ blast was executed with two passes of a "K1" nozzle on a "Snow Jet" machine by Applied Surface Technologies Co.

The HCl etch was performed by immersion at 71°C for 3.5 minutes in 10%HCl/90%Distilled Water followed by a distilled water rinse.

The test buttons were assembled as shown in Figure 27 and impregnated.

Two dimensional weave S-2 Fiberglas (BFG Industries Inc., style 6781, 8 harness satin weave with 558 finish sizing) was used between the coupons of the button. CTD101K (Composite Technology Development Inc.) resin was mixed in the manufacturer's recommended proportions of 52.2% resin/47% hardener/0.8% accelerator.

The buttons were assembled in the tooling fixture shown in Figure 28. The tooling was coated with 'Freecote 44' (Dexter Corp.) prior to assembly as a parting agent. The blended CTD101K was slowly hand blended to minimize air entrapment while being heated from room temperature to 60°C. It was then placed in a vacuum chamber and degassed under 26.5" of vacuum for one hour. While still under vacuum it was transferred to a holding tray and thereby immersing the buttons and tooling fixture.

The holding tray was removed from the vacuum chamber, placed in a pressure chamber and pressurized to 90 psi for 15 minutes.

The pressure chamber was returned to ambient pressure and the handling tray was transferred to a curing oven.

The tooling and coupons were cured per the manufacturer's recommendation at 110°C for 5 hours followed by 125°C for 16 hours.

The tooling was disassembled and the test buttons removed. Because of flow of the resin into fine interstices and crevices under pressure, it was necessary to mill part of the tooling to complete disassembly. Figures 28 and 29 are in process photographs illustrating this coupon removal. Some test buttons were damaged in this disassembly process (these are footnoted on the results table.)

The test buttons were tested for shear strength under a compressive load. (the buttons were loaded on a 45° angle). Figure 30 is a schematic of the loading fixture used in this testing.

The detailed test report, RDD:96:43346-001:01 May 22, 1995, covers this stage 2 testing and is included as attachment 1 to this SDRL.

INCOLOY-908 TEST COUPON CONFIGURATION

Figure 25. Test Coupon for Compression Shear and Reaction Bonding Experimentation

TEST BUTTON FOR COMPRESSION SHEAR TEST

Figure 26. Compression Shear Button

Figure 27. In Process Removal of Test Coupons

Figure 28. In Process Removal of Coupons

SCHEMATIC DIAGRAM
OF
COMPRESSION/SHEAR
FIXTURE

Figure 29. Test Fixture

Table 6

First Campaign:		
Room Temperature Shear Compression Test Results		
Sample Preparation	Shear Str. (psi)	Avg. Shear Str. of Pair (psi)
1. Alcohol Wipe (Control)	a 6412	3286
	b 159	
2. HCl Etch Water Rinse	a 8004	7257
	b 6510	
3. CO ₂ Blast Only	a 4557	5668
	b 6780	
4. Grit Blast Alcohol Wipe	a 756	1072
	b 1387	
5. Scotch Brite/ Alcohol Scrub	a 2756	(2)2756
	b --(1)	
6. Mech. Method #1 and Air	a --(1)	(2)8393
	b 8393	
7. Mech. Method #1 and CO ₂	a 5213	5272
	b 5331	
8. Mech. Method #6 and Air	a 5606	5618
	b 5629	
9. Mech. Method #6 and CO ₂	a 3072	1569
	b 65	
10. Mech. Method #9 and Air	a 8770	6720
	b 4670	
11. Mech. Method #9 and CO ₂	a 231	162
	b 93	

(1) Sample damaged during removal from impregnation fixture.

(2) One sample only

5.5 Stage 3 Experimentation Results: Second Series of Compression/Shear samples.

After reviewing the results of the first campaign room temperature survey of compressive strength, the following specimens were selected for additional testing at either room temperature or cryogenic (77K) testing or both.

The detailed test report, RDD:96:43421-001:01, August 8, 1995 covers this stage 3 testing and is included as attachment 2 to this SDRL.

Table 7

Second Campaign: Room and Cryogenic Temperature Shear Compression Test Results			
Sample Preparation	Temp	Shear Str. (psi)	Avg. Shear Str. of Set (psi)
1. Alcohol Wipe (Control)	a RT (21°C)	5875	5348
	b RT	4822	
	c Cryo (77°K)	5918	8800
	d Cryo	11681	
2. HCl Etch Water Rinse	a Cryo	(1)11208	11374
	b Cryo	11540	
3. CO ₂ Blast Only	a RT	2627	4142
	b RT	5657	
	c Cryo	2490	4581
	d Cryo	6671	
6. Mech. Method #1 and Air	a RT	3672	3257
	b RT	(1)2843	
	c Cryo	6377	6587
	d Cryo	8061	
	e Cryo	7813	
	f Cryo	4096	
8. Mech. Method #6 and Air	a RT	1418	2602
	b RT	3785	
	c Cryo	(1)5462	5555
	d Cryo	7898	
	e Cryo	4431	
	f Cryo	4431	

(1) These values are failure on a second cycle. The specimen had survived a higher load on first cycle.

The sample preparation technique was the same as for the initial survey except for revisions of the tooling to eliminate the need for milling to remove the test buttons. This revision was successful to the extent that no buttons were damaged and machine removal was not required.

5.6 Conclusions:

A review of tables 6 and 7 reveals that acid etching is the most consistent and highest strength bond preparation of those attempted. This technique can be considered a 'gold standard' by which other techniques can be judged but would be inordinately expensive and hazardous to execute in production.

CO₂ cleaning, as executed in this experiment demonstrates no contribution to bond enhancement as compared to an alcohol wipe on the control specimens or as a cleanup after mechanical cleaning when compared to an air blow off. It should be noted that the CO₂ cleaning system used in this experiment is a light duty machine and that more aggressive CO₂ cleaning systems are available.

The strength of the epoxy bond to conductor is enhanced at the cryogenic test temperature as compared to room temperature. Although variable, an increase of approximately 40% in strength is noted in going from room temperature to 77°K.

Mechanical cleaning methods 1 (120 grit Al₂O₃ grit flap wheel) and 6 (80 grit SiC filament wheel) both result in a fairly high strength consistent bonding surface which is compatible with the configuration of the TPX coils for post reaction processing. Either cleaning technique could be incorporated into cleaning tooling.

The use of an alcohol wipe after reaction processing to assure mechanical cleanliness of the as reacted surface does not result in a particularly low strength bond. (The 159psi sample may represent unobserved damage from coupon removal from the tooling and may thus well be an outlier.)

LRC-254

Babcock & Wilcox
a McDermott company

Research and Development Division
Lynchburg Research Center
Lynchburg, Virginia

To	K. C. EWING (80A) - A&MS, NNFD	
From	T. N. ACKERSON (750) - MATERIALS PROCESSING, LRC	
Cust.		File no. RDD:96:43346-001:01
Subj.	SHEAR TESTING OF TPX EPOXY JOINTS	Date MAY 22, 1995

This letter to cover one customer and one subject only.

SUMMARY

The Accelerator & Magnet Systems Division requested LRC to perform shear testing on 22 TPX magnet test samples. The samples consisted of two Incoloy 908 wafers joined with a layer of epoxy. The Incoloy substrates exhibited various surface preparations thought to affect epoxy adherence. This workscope included the design and fabrication of a test fixture capable of performing 45° compressive shear tests on the sandwich-like specimens at both room and liquid nitrogen (cryogenic) temperatures. The tests for this workscope were performed at room temperature using an Instron servo-hydraulic testing machine. Acceptable test results were achieved, with shear strengths averaging approximately 5,000 psi and a maximum approaching 9,000 psi. These test results will allow A&MS to further define their surface preparation matrix for the next round of tests which may be conducted under cryogenic conditions.

KEY WORDS: MAGNETS, CONDUIT, SHEAR TESTING, CRYOGENIC TESTING

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INTRODUCTION

The Babcock & Wilcox Accelerator & Magnet Systems (A&MS) Division is in the process of determining methods of optimizing CTD101K (a type of epoxy chosen by A&MS) adhesion to Incoloy 908 (nickel base superalloy) substrates. Initial efforts by A&MS have concentrated on surface modification/preparation of the substrate material such as chemical cleaning and grit blasting.

A&MS fabricated 22 test specimens for this initial workscope. The specimens resembled sandwiches as shown below. The 22 samples were broken down into 11 sample pairs, each pair representing a different surface preparation method.

LRC was asked to design and fabricate a test fixture which would be capable of compression shear testing samples, in tandem, at either room temperature or that of liquid nitrogen. The workscope also included actual room temperature testing of the 22 specimens.

All work related to this project was conducted in accordance with *Standard Practice*, the baseline quality level within the Research & Development Division.

METHODOLOGY

The shear test fixture was designed by LRC based on fixtures already used in the cryogenic testing industry (reference). The type 304 stainless steel and G-10 (fiber/epoxy composite) fixture, shown schematically in Appendix A, allows for simultaneous testing of two specimens at a 45° angle. All tests in this workscope were conducted at room temperature using an Instron 8500 servo-hydraulic mechanical tester. An R&D Technical Procedure, LRC-TP-632, was prepared specifically for these tests and was approved by A&MS.

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The specimens were provided by A&MS in a ready-to-test condition. Each of the 11 pairs represented various surface preparations of the Incoloy 908 as outlined in the schedule provided in Appendix B. Two of the specimens, 5.b and 6.a were damaged upon removal from epoxy curing and were not tested. All testing was conducted in accordance with LRC-TP-632 by the author. Specific details of the test methodology are covered in LRC-TP-632 and are not discussed in this report.

Each test was performed at a displacement rate of 0.005" per minute. As each test proceeded, load and displacement data was acquired by the computer at a rate of 4 points per second and stored on diskette. In no case did both samples fail simultaneously during the tandem tests. This dictated the use of a solid 304 stainless steel dummy sample in lieu of the failed sample, as prescribed in the technical procedure.

Test data was later imported into a spreadsheet program where shear strength was calculated according to the following equation:

$$\tau = (P_{\max}/A) \sin \theta$$

where τ = Shear Strength
 P = Maximum load (lbs)
 A = Sample Area (in²) = 0.178 in²
 θ = Test angle = 45°

Additionally, the raw displacement data was adjusted based on *load train compliance* which was measured prior to performing the tests. The compliance test consisted of installing 2 solid 304 stainless steel dummy samples into the test fixture and loading up to 3500 lbs. The material used in fabricating metallic portions of the test fixture, type 304 stainless steel, was re-specified by the author from the original Inconel 718 in order to ease machinability and reduce costs. During compliance testing, however, it was observed that the elastic limits of the fixture (~3500 lb shear compressive load) were close to being realized. Minor plastic deformation of parts of the test fixture dictated re-machining of the sample cups. The machining did not affect test data.

In addition to being corrected for system compliance, the displacement data was also set to zero at the point which the compressive load reached 25 lbs. (e.g., the test specimens were firmly seated in the test fixture yet had not undergone any deformation).

Shear stress vs. corrected displacement plots were generated for each specimen which failed at a measureable load. The plots were not linear, suggesting a varying shear modulus. The modulus, therefore, was not calculated.

RESULTS

The majority of the test specimens failed in a brittle manner as was expected. Some, however, sheared apart slowly with little resistance under negligible loading. None of the specimen pairs failed simultaneously, which effectively doubled the number of tests performed (e.g., initial tandem test *plus* additional test with 304 stainless dummy).

Table 1 provides maximum load, shear strength, and displacement at failure data for each specimen. These results are also shown graphically in Figures 2 and 3. "N/A" in the table indicates samples that were either not tested or failed at negligible loads (1.b, 9.b, 11.a, 11.b, 5.b, and 6.a). Note that the samples which did not fail during the initial tandem test (1.a, 2.a, 3.b, 4.b, 7.b, 8.b, 9.a, and 10.a) did not exhibit bond degradation during the initial test. In other words, they failed at loads higher than those realized during the initial tandem test.

Shear stress vs. displacement plots are provided in Appendix C. The curved nature of the typical shear stress vs. displacement plot suggests the epoxy gives slightly at minor loads, indicating ductility. At higher loads, however, displacement is inhibited and the joint fails in a brittle manner:

Figure 1. Typical Shear Stress vs. Displacement Curve

Table 1. Shear Compression Test Results

Sample ID	Max Load (psi)	Shear Str. (psi)	Avg. Shear Strength of Sample Pair (psi)	Displacement at Failure, in
1.a	9068	6412	3286	0.032
1.b	225	159		N/A
2.a	11320	8004	7257	0.031
2.b	9207	6510		0.028
3.a	6445	4557	5668	0.010
3.b	9588	6780		0.013
4.a	1069	756	1072	0.008
4.b	1962	1387		0.010
5.a	3898	2756	2756	0.010
5.b	N/A	N/A		N/A
6.a	N/A	N/A	8393	N/A
6.b	11870	8393		0.015
7.a	7372	5213	5272	0.014
7.b	7539	5331		0.005
8.a	7928	5606	5618	0.012
8.b	7961	5629		0.010
9.a	4345	3072	1569	0.007
9.b	92	65		N/A
10.a	12403	8770	6720	0.007
10.b	6605	4670		0.009
11.a	327	231	162	N/A
11.b	132	93		N/A

Samples 1.b, 9.b, 11.a, and 11.b failed via slip at negligible loads (< 50 lb)

Figure 2. Shear Strength of Epoxy Joints (at failure)

Figure 3. Displacement of Epoxy Joints (at failure)
(Note: Displacement at failure data is reported only for samples that sheared normally at high loads)

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CONCLUSIONS

The series of tests performed in this workscope proved the feasibility of carrying out such tests at LRC, which was one goal of this project.

Conclusions that can be drawn from the tests are as follows:

- sample sets 2 and 10 provided the highest *average* shear strengths
- sample 10.a exhibited the highest individual shear strength of 8770 psi
- sample sets 7 and 8 exhibited excellent sample-to-sample agreement in shear strength values
- sample set 11 performed poorly with negligible shear strength
- stresses of the initial test, for those that passed the initial test, did not appear to degrade the shear strength when tested with a dummy
- the epoxy appears to be most compliant under low-to-moderate shear loading, then transitions to strong/brittle behavior at higher loads.

RECOMMENDATIONS

Due to a cost-saving design change (material choice), the elastic limits of the test fixture were approached by some of the stronger test specimens. Although they did not reach that limit (~3,500 lbs), it is recommended that a stronger material be investigated for possible use in future tests.

ACKNOWLEDGEMENTS

The author greatly appreciates the assistance of Steve Clark (NDM&D) for the final design and fabrication of the test fixture.

REFERENCE

R. P. Reed et al., Advances in Cryogenic Engineering Materials, Vol. 40B, Plenum Press, p. 1009.

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Prepared by:

T. N. Ackerson - LRC
Materials Processing Section

Approved by:

H. H. Moeller - LRC
Manager, Materials Processing Section

APPENDIX A:
Schematic of Test Fixture

PROCEDURE #: LRC-TP-632
REV. #: 0

PAGE 8
DATE: 2/21/95

← Upper G10 Assembly

← Bushing

← Positioning Screws (3)

← Lower G10 Assembly

APPENDIX B:
Surface Preparation Test Matrix

4/20/95

Test Coupon Grid Locations

	A	B	C	D	E
1	☐	☐	☐	☐	☐
2	☐	☐	☒	☐	☐
3	☐	☐	☒	☐	☐
4	☐	☐	☒	☐	☐
5	☐	☐	☐	☐	☐

GRID	SAMPLE	
LOCATION	ID	Sample Description
A-1	1.a	Control Sample no cleaning
A-2	1.b	Control Sample no cleaning
A-3	2.a	Chem. Etching *1
A-4	2.b	Chem. Etching *1
A-5	3.a	CO ₂ Blast
B-1	3.b	CO ₂ Blast
B-2	4.a	AL203 220 Grit Blast
B-3	4.b	AL203 220 Grit Blast
B-4	5.a	ScotchBrite & Alcohol Wipe
B-5	5.b	ScotchBrite & Alcohol Wipe
C-1	6.a	Cleaning Technique #1 followed by air blast
C-2	empty	
C-3	empty	
C-4	empty	
C-5	6.b	Cleaning Technique #1 followed by air blast
D-1	7.a	Cleaning Technique #1 followed by CO ₂ blast
D-2	7.b	Cleaning Technique #1 followed by CO ₂ blast
D-3	8.a	Cleaning Technique #6 followed by air blast
D-4	8.b	Cleaning Technique #6 followed by air blast
D-5	9.a	Cleaning Technique #6 followed by CO ₂ blast
E-1	9.b	Cleaning Technique #6 followed by CO ₂ blast
E-2	10.a	Cleaning Technique #9 followed by air blast
E-3	10.b	Cleaning Technique #9 followed by air blast
E-4	11.a	Cleaning Technique #9 followed by CO ₂ blast
E-5	11.b	Cleaning Technique #9 followed by CO ₂ blast

Damaged →
Damaged →

*1 Chem Etching solution :

Hydrochloric Acid 10% DI H₂O 90%

APPENDIX C:
Shear Stress/Displacement Curves

Shear Stress vs. Corrected Displacement, Sample #1.a

Shear Stress vs. Corrected Displacement, Sample #2.b

Shear Stress vs. Corrected Displacement, Sample #3.a

Shear Stress vs. Corrected Displacement, Sample #3.b

Shear Stress vs. Corrected Displacement, Sample #4.a

Shear Stress vs. Corrected Displacement, Sample #4.b

Shear Stress vs. Corrected Displacement, Sample #5.a

Shear Stress vs. Corrected Displacement, Sample #6.b

Shear Stress vs. Corrected Displacement, Sample #7.a

Shear Stress vs. Corrected Displacement, Sample #7.b

Shear Stress vs. Corrected Displacement, Sample #8.a

Shear Stress vs. Corrected Displacement, Sample #8.b

Shear Stress vs. Corrected Displacement, Sample #9.a

Shear Stress vs. Corrected Displacement, Sample #10.a

Shear Stress vs. Corrected Displacement, Sample #10.b

LRC-204

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Lynchburg Research Center
Lynchburg, Virginia

To	K. C. EWING (80A) - A&MS, NNFD	
From	T. N. ACKERSON (750) - MATERIALS PROCESSING, LRC	
Cust.		File no. RDD:96:43421-001:01
Subj.	ADDITIONAL SHEAR TESTING OF TPX EPOXY JOINTS	Date AUGUST 8, 1995

This letter to cover one customer and one subject only.

SUMMARY

LRC has performed shear testing on an additional 22 TPX magnet test samples for Accelerator & Magnet Systems (A&MS) of NNFD. As in the previous workscope¹, the samples consisted of two Incoloy 908 wafers joined with a layer of epoxy. The epoxy layer also contained a thin film of 2-dimensionally woven fiberglass. The Incoloy wafers underwent various surface modifications which were thought to affect epoxy adherence. This follow-up workscope included both room temperature and cryogenic (liquid nitrogen, 77K) shear testing using an Instron servo-hydraulic testing machine. Test results showed that the specimens were generally stronger at cryogenic temperatures (compared to room temperature) and exhibited shear strengths as high as 11,540 psi.

KEY WORDS: MAGNETS, CONDUIT, SHEAR TESTING, CRYOGENIC TESTING.

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INTRODUCTION

The Babcock & Wilcox Accelerator & Magnet Systems (A&MS) group is in the process of determining methods of optimizing CTD101K (a type of epoxy chosen by A&MS) adhesion to Incoloy 908 (nickel base superalloy) substrates. Initial efforts by A&MS have concentrated on surface modification/preparation of the substrate material such as chemical cleaning and grit blasting.

For the initial round of testing described in a previous R&DD report¹, A&MS fabricated 22 test specimens which resembled sandwiches as shown below. The 22 samples were broken down into 11 sample pairs, each pair representing a different surface preparation method.

The 45° shear compression tests in the original workscope were conducted at room temperature only. For this follow-up workscope, an additional 22 test specimens were fabricated by A&MS and were tested at either room or cryogenic (77K) temperatures.

All work related to this project was conducted in accordance with *Standard Practice*, the baseline quality level within the Research & Development Division.

METHODOLOGY

The shear test fixture was designed by LRC based on fixtures already used in the cryogenic testing industry². The type 304 stainless steel and G-10 (fiber/epoxy composite) fixture allows for simultaneous testing of two specimens at a 45° angle. All tests in this workscope were conducted using an Instron 8500 servo-hydraulic mechanical tester with fully digital controls. An R&D Technical Procedure, LRC-TP-632, was prepared specifically for these tests and was approved by A&MS.

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The specimens were provided by A&MS in a ready-to-test condition. Each of the 11 pairs represented various surface preparations of the Incoloy 908 as outlined in the schedule provided in Appendix A. All testing was conducted in accordance with LRC-TP-632 by the author. Because the procedure was written for room temperature tests only, the following additional steps were taken for the cryogenic testing:

- 1) Once the specimens were installed per LRC-TP-632, the cryostat was installed on the Instron's lower ram as shown in Figure 1.
- 2) The upper fixture/load cell was lowered to a point approximately 0.25 " above the test fixture, then the lid was clamped onto the cryostat.
- 3) A Type T thermocouple was inserted through the lid of the cryostat (see Figure 2). The thermocouple tip was at a level above the test specimens such that a reading of -6.1 mV (- ~77K) or lower would indicate total test fixture immersion in liquid nitrogen.
- 4) The Instron actuator was activated, and the lower ram was brought up until a 25-50 lb. preload was on the samples.
- 5) The cryostat was backfilled with liquid nitrogen until the multimeter gave a reading of approximately -6mV.
- 6) The test was initiated via the Instron computer controls.

Figure 1. Overall View of Cryostat on Instron Servo-Hydraulic Tester

Figure 2. Detail of Cryostat Lid Showing LN2 Hose and Type T Thermocouple

Each test was performed at a displacement rate of 0.005" per minute. As each test proceeded, load and displacement data were acquired by the computer at a rate of 3 points per second and stored on diskette. When only one of the two tandem specimens failed, a solid 304 stainless steel dummy sample was used in lieu of the failed sample, as prescribed in the technical procedure, and the test was repeated.

Additional details of the shear test procedure are provided in LRC-TP-632 and are not described in this report.

Test data were later imported into a spreadsheet program where shear strength was calculated according to the following equation:

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$$\tau = (P_{\max}/A) \sin \theta$$

where τ = Shear Strength
P = Maximum load (lbs)
A = Sample Area (in²) = 0.178 in²
 θ = Test angle = 45°

Additionally, the raw displacement data were adjusted based on *load train compliance* which was measured prior to performing the tests. In addition to being corrected for system compliance, the displacement data were also set to zero at the point where the compressive load reached 25 lbs. (i.e., the test specimens were firmly seated in the test fixture, yet had not undergone any significant deformation).

Although the test fixture was immersed in LN₂ prior to beginning the tests, slight test fixture shrinkage likely continued throughout the duration of the tests. No displacement correction was made for this shrinkage, which did not affect load-related data.

RESULTS

Table 1 provides maximum load, shear strength, and corrected displacement at failure data for each specimen. These results are also shown graphically in Figures 3 and 4. In general, the samples exhibit higher shear strengths at cryogenic temperatures.

Samples 17-A, 14-A, and 21-A failed at lower stresses during their second test with the stainless steel dummy. However, the majority of the specimens tested with a dummy failed at loads higher than those realized during their initial tandem test. This indicates that in general, there was little or no bond degradation resulting from the thermal and loading cycles of the initial tests

As mentioned previously, a caveat must be issued regarding the cryogenic test displacement data. No correction was made for test fixture shrinkage, which may explain the larger displacements reported for the cold tests. This behavior did not affect the shear stress data.

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Table 1. Shear Compression Test Results

TPX Shear Testing II
Project #43421

Sample ID	Temp, K	Max Load (psi)	Shear Str. (psi)	Avg. Shear Strength of Sample Pair (psi)	Displacement at Failure, in
12-A	294	8308	5875	5348	0.011
12-B	294	6820	4822		0.021
15-A	294	3715	2627	4142	0.008
15-B	294	8000	5657		0.008
17-A	294	5193	3672	3257	0.010
17-B	294	4020	2843		0.006
20-A	294	2006	1418	2602	0.008
20-B	294	5353	3785		0.008
13-A	77	8369	5918	8800	0.043
13-B	77	16520	11681		0.042
14-A	77	15850	11208	11374	0.042
14-B	77	16320	11540		0.054
16-A	77	3521	2490	4581	0.011
16-B	77	9435	6671		0.027
18-A	77	9019	6377	7219	0.006
18-B	77	11400	8061		0.011
19-A	77	11050	7813	5954	0.053
19-B	77	5792	4096		0.030
21-A	77	7724	5462	6680	0.014
21-B	77	11170	7898		0.031
22-A	77	6267	4431	4431	0.038
22-B	77	6267	4431		0.038

Shaded cells indicate coupon which failed first
22-A and 22-B Failed Simultaneously

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Figure 3. Shear Strength of Epoxy Joints (at failure)

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Figure 4. Displacement of Epoxy Joints (at failure)

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CONCLUSIONS

The following can be concluded from this workscope:

- The epoxy joints exhibited generally higher shear strengths at 77K than at room temperature (294K)
- Sample set 14 (chemically etched) exhibited the highest average shear strength of 11,375 psi. The same cleaning technique resulted in the highest shear strength during the earlier workscope as well (Samples 2-A&B).

REFERENCES

1. T. N. Ackerson, R&DD Letter Report #RDD:96:43346-001:01, "Shear Testing of TPX Epoxy Joints," May 22, 1995.
2. R. P. Reed et al., Advances in Cryogenic Engineering Materials, Vol. 40B, Plenum Press, p. 1009.

Prepared by:

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Materials Processing Section

Approved by:

H. H. Moeller - LRC
Manager, Materials Processing Section

APPENDIX A:
Surface Preparation Test Matrix

Grid		Sample	ROOM TEMP.	COLD
Location	SAMPLE DESCRIPTION	ID	TEST	TEST
A-1	Control Sample no cleaning	12-A	YES ✓	
A-2	Control Sample no cleaning	12-B	YES ✓	
A-3	Control Sample no cleaning	13-A		YES ✓
A-4	Control Sample no cleaning	13-B		YES ✓
A-5	Chemical Etching *1	14-A		YES ✓
B-1	Chemical Etching *1	14-B		YES ✓
B-2	CO2 Blast	15-A	YES ✓	
B-3	CO2 Blast	15-B	YES ✓	
B-4	CO2 Blast	16-A		YES ✓
B-5	CO2 Blast	16-B		YES ✓
C-1	Cleaning Technique #1 followed by air blast	17-A	YES ✓	
C-5	Cleaning Technique #1 followed by air blast	17-B	YES ✓	
D-1	Cleaning Technique #1 followed by air blast	18-A		YES ✓
D-2	Cleaning Technique #1 followed by air blast	18-B		YES ✓
D-3	Cleaning Technique #1 followed by air blast	19-A		YES ✓
D-4	Cleaning Technique #1 followed by air blast	19-B		YES ✓
D-5	Cleaning Technique #6 followed by air blast	20-A	YES ✓	
E-1	Cleaning Technique #6 followed by air blast	20-B	YES ✓	
E-2	Cleaning Technique #6 followed by air blast	21-A		YES
E-3	Cleaning Technique #6 followed by air blast	21-B		YES
E-4	Cleaning Technique #6 followed by air blast	22-A		YES
E-5	Cleaning Technique #6 followed by air blast	22-B		YES

*1 Chemical Etching Solution:
Hydrochloric Acid 10% DI H₂O 90%

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT AND MANUFACTURE

Contract B235308

SDRL 37B

Bending Development

August 18, 1995

13-950814-BW-HBell-01

Babcock & Wilcox
Accelerator & Magnet Systems
PO Box 785
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Lynchburg, VA 24505

Approved for Submittal by:
C.M. Weber, TPX Project Mgr.

BENDING DEVELOPMENT FINAL REPORT
for the
TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

PRELIMINARY DESIGN REVIEW

SDRL 37B
13-950814-BW-HBell-01

Prepared for the University of California
Lawrence Livermore National Laboratory
Subcontract B235308

Prepared by the Babcock & Wilcox Company
NNFD, Accelerator and Magnet Systems
Mt. Athos Road, Lynchburg, VA 24505

1. INTRODUCTION

This document is intended to address the contract requirement for forming property investigation and research, as required in the applicable Technical Statement of Work:

TSOW §1.3.15.2... Conductor Forming "This task includes the activities needed to understand and define the bending properties and limitations for both the unreacted as well as reacted sheathed conductors. Conductor overbending required to counteract springback as well as relaxation and dimensional changes after reaction should be addressed."

This report summarizes the findings of the TPX Phase I bending development program. This detailed program plan can be found in Appendix I of this document. The data included in this report are not all-inclusive, but the findings and the significant representative data are included. Examples, photographs, and sketches are included where appropriate.

2. OVERVIEW OF BENDING PROGRAM

The TPX bending development program has been very successful in fulfilling its original intent. The three roll bender that B&W procured to satisfy the requirements of this study and the radius gauge B&W designed and procured, provided significant insight into the requirements of production tooling for the TPX winding machine. The lead bending fixture and the simple measurement device used to inspect the results of those bends yielded a wealth of knowledge regarding lead bending conduit. The feasibility of winding the TF coils and producing the manual bends on those coils was established.

The limitations of the simple roll bender helped to highlight, as reported in Section 5.2, capabilities that a coil winding machine should possess. Considerations such as tooling rigidity and rolls that closely fit the contour of the conduit being formed are shown in terms of the results yielded by simple modifications to the 3 roll bender which yielded significant results..

NOTE:

In *TSOW §1.3.15.2*, the study of unreacted as well as reacted conductor is mentioned. The bending of reacted conductor was dropped due to the unavailability of superconducting cable until Phase II of the TPX program. Studying the bending characteristics of the reacted conductor was only meaningful if superconductor was present, so strand damage could be assessed.

3. MATERIALS

The bending development program has been largely driven by the availability of Government Furnished Material (GFM) conductor. TF conduit in particular was in extremely short supply. This shortage of material availability precluded the performance of experiments on

statistically significant sample sizes, but inferences can be drawn from the program data to establish a starting point for tool design and process qualification.

3.1 Source

Conduit and simulated conductor material used in the bending development work was provided by LLNL as part of the contract, with the exception of the commercial stainless steel conduit used for preliminary bend work.

CS Mockups I-908 Conduit

This CICC was excess from a Westinghouse CS coil winding mockup and was received at B&W in the form of a 100 in. dia. coil (one turn per layer) on a wooden shipping pallet with radial supports. The tubing was fabricated from annealed strip stock, seam welded, annealed and rounded. The resultant 40 ft. lengths were butt welded to form the ordered length. The butt welds were not annealed. The copper strands were pulled through the round tubing. The tubing was then squared up. The finished CICC was coiled for shipment. It had a dark color. Approximately 370 feet were received at B&W.

TF Mockups I-908 Conduit

Empty: This conduit was received in two shipments for a total of 551 ft. All but two pieces (approx. 90 ft.) were seamless, extruded, annealed and pickled rounds which were then squared up. It was then cut into straight shipping lengths. The two pieces were seam welded tubing.

Figure 1. Nominal Dimensions for CS, PF, and TF Conduit

Simulated Conductor: This CICC was received in one shipment in straight lengths, for a total of total of 180 ft. It was seamless, extruded, annealed, and pickled as rounds. Copper strands (Filler, approximately, 360 strands) were pulled through the rounds. The CICC was then squared up and sent to B&W. The number of copper strands and the cable dimensions indicate that it was CS cable. This raises some concerns about the packing factor of copper in the conduit, being atypical, might impact bending results. In subsequent trials, empty conduit did display different characteristics than simulated conductor.

PF Mockups 316LN Conduit

This CICC was received in straight lengths for a total of 115 ft. The tubing was seamless, extruded, annealed and passivated. The copper strands were pulled through the rounds. The CICC was squared up and shipped to B&W.

Stainless Steel

Prior to the arrival of TPX materials, 304 stainless steel, one inch square, 0.120 in. wall tubing, procured by B&W (ASTM A 554 90) was roll formed first at the B&W Alliance, Ohio Research Center and later at the Lynchburg, Va. magnet facility. This early work was useful in preliminary parameter development. Insight was gained by personnel regarding the response of tubing to roll forming and lead bending. Also, insight was gained regarding the tooling, equipment, and inspection methods that would be required for subsequent development efforts.

3.2 Hardness

Hardness values of the materials used during the bending development varied significantly. The data presented in the individual sections on roll forming and bench bending reflected significant variability in the conduit supplied. The problems encountered tended to be within piece hardness variability (this data is presented in the applicable sections). The effect is much more pronounced in the roll bending operations since the bends are gentler because of the larger radii. Initially, it was thought that the conduit was not giving a true reading because of its geometry. To verify that the readings were genuine, we processed a verification mock-up (ref. Figure 2).

Figure 2. Hardness Data Validity Mock-up

COMPRESSION EFFECT
ON
MEASURED HARDNESS

DATA

SIDE	LOCATION	TUBE	WALL
A	1	C20	C20
A	2	C22	C20
A	3	B98	B100
A	4	C22	C21
A	5	C21	C20
A	6	B97	B98
A	7	B99	C21
A	8	C22	C21
A	9	B97	B98
B	1	B98	B98
B	2	C23	C22
B	3	B96	B96
B	4	C20	B97
B	5	C21	C20
B	6	B95	B95
B	7	C21	B99
B	8	C22	C23
B	9	B97	B95

PURPOSE:

DETERMINE IF LOADS APPLIED BY ROCKWELL
HARDNESS TESTER DEFLECT THE CONDUIT
WALL YIELDING FALSE HARDNESS VALUES.

TECHNIQUE:

MEASURE THE HARDNESS ON TWO WALLS OF
THE CONDUIT AND AGAIN AT THE SAME SITES
AFTER REMOVAL OF THE WALLS FROM THE
SAMPLE.

CONCLUSION:

NO SIGNIFICANT DIFFERENCE WAS DETECTED
BETWEEN THE CONDUIT HARDNESS READINGS
AND THE WALL SAMPLE HARDNESS READINGS.

IT IS FEASIBLE THAT HARDNESS READINGS ARE
USEFUL IN CHARACTERIZING PRODUCTION CICC
WHEN TAKEN ON THE OUTSIDE OF TF CICC.

NOTE : ROCKWELL B100 IS APPROXIMATELY
EQUIVALENT TO ROCKWELL C23.

3.3 Development

The natural extension of the bending development program would be an abbreviated bending development program utilizing real CICC to verify physical bend properties and strand sensitivity after reaction with production grade material. As more Nb₃Sn becomes available during Phase II, this should be considered.

4. BENCH BENDING

The bench bending program embraces all discreet mechanical bends for leads and transitions within the TF, PF, and CS magnet systems. A simple fixture (ref. Figure 3) was used to perform each of the bending operation.

4.1 Lead Bending Fixture / Technique

Figure 3. Bench Bending Fixture

Figure 4. Data Capture on Conduit/Conductor Inspection

Technique:

1. Conductor was placed into the bench bender and pressed to a particular angle.
2. Location of the bent conductor's O.D. was marked.
3. The loaded included angle and hydraulic pressure were measured and recorded.
4. Hydraulic pressure was released.
5. The spring back and unloaded included angle were measured and recorded.

6. Steps 2-5 were repeated for each angle that the conductor was pressed to.

Each conductor sample was pressed to 3-5 different angles and each of the pressed angles gave us another point on the spring back curve. The loaded and unloaded included angles were plotted on a graph and a trend line was fitted to this array using the method of least squares. Displayed on these curves are the spring back formulas and the confidence factors.

These graphs are attached and each includes the following:

1. Unique description of the conduit dimensions and material. Refer to drawings (Figure 3. Bench Bending Fixture, Figure 4. Data Capture on Conduit/Conductor Inspection,) attached.
2. Condition of conduit when bent.
3. Reference to mock-up number referenced on attached matrix of projects.
4. Spring back formula.
5. Confidence factor.
6. Direction of bend.
7. Radius of bending die.

Data Obtained:

1. With these formula's the amount of overbend required can be calculated for any angle with any one of the 24 conditions defined by curves 1 through 24.
2. Comparison of two or more of these curves will give the effect on bending characteristics due to differences in material, dimensions and techniques.
3. We have plotted a multiple number of curves on each of (12) charts, each configured to quantify the effect on bending characteristics of a particular variation. See attached charts (1 through 12)
4. The cross sectional details as defined by Figure 3 and Figure 4, were measured before and after each of the bends. Cross sectional data was also taken on a representative sample of each material type before and after the reaction cycle.

This data is recorded in Tables 1-6.

4.2 Lead Bending Data Summary

Lead bending provided a good basis for establishing production tooling design criteria. The results achieved were consistent with the revised bending plan and the analytical work done previously. The minimum practical radii for CS conduit of 7.5" was established in support of the CS roll forming operation..

4.2.1 BENDING CHARACTERISTICS

4.2.1.1 Springback & Minimum Radii

The data from the study of die size on springback for CS (ref. Figure 7), TF hard way bends (ref. Figure 6), and TF easy way bends (Figure 8) are presented to contrast the effects of differences in bend radii. There is an indication that, while the resulting springback curves continue to be linear and predictable, the amount of springback must be predicted on the basis of the material and the die radius. The springback does vary between bend radii for both the easy way and hard way bends.

4.2.1.2 Repeatability

Refer to: Figure 10 (compares CS 1, CS 2 and CS 3-all bent with a 6" radius die)

Figure 10 (compares CS 4 and CS 5-all bent with a 7.5" radius die)

Figure 11 (compares CS 6 and CS 7-all bent with a 9" radius die)

Evaluation:

1. In the expected working range the total spring back is very repeatable. Repeatability is better for the 7.5" and 9" dies than for the 6" die. This indicates that CS bending radii should not be 6" or less as it lacks repeatability..

Figure 12. Repeatability Testing with CS Simulated Conductor - 6\" Die

Data Obtained:

1. Confirmed that repeatability is better when yielding is greater.

4.2.1.3 Keystoning

Some deformation of the conduit cross section occurred during bending trials. The empty conduit was the most prone to this problem. Section 5.3.1.3 has illustrations of how the phenomena affects the cross sectional profile. The 6 inch dies produced an intolerable amount of keystoning during lead bending. With the 7.5\" dies the keystoning was noticeable but did not block the flow paths around the conductor. When using the 9\" die set the keystoning was negligible. Quantification of this keystoning is presented in Section 5.3.1.3.

4.2.1.4 Weld Seam Orientation

Figure 13 presents the results from the weld seam orientation bending trials. There is very little difference in the spring back formulas for (CS 8) and (CS 10). These two samples were bent with the seam in the same plane as the plane of the bend. One had the seam on the inside of the

bend, the other had its seam on the outside of the bend. The results and formula for CS 9, where the weld seam was at 90° to the plane of the bend, are markedly different. The formula for (CS 9) has a higher constant and a lower slope. The amount of twist induced in the bending of CS-9 was also noticeably higher. This is most likely due to inconsistent location of weld seams relative to the conduit cross section.

4.2.1.5 Effects of Coil Set

Purpose: The coil set study was developed to gain knowledge regarding the impact of winding and unwinding the coil. The majority of the CS conduit was received on a roll. This study was designed to uncover problems with our data related to consistency in the amount of bend in the conductor initially. CS 1, 2, and 3 varied from each other significantly in springback. CS-23 was a mockup bent in the opposite direction (i.e., opposite the direction of the original radius).

4.2.1.6 Hard Way vs. Easy Way Bending

Hard way bending was compared to easy way bends was to determine any significant difference in springback. The results presented in Figure 15 indicates that the hard way bends have more plastic deformation due to more yield in the external fibers. This is evident from the steeper slope of the hard way bend. This is consistent with analytical results. More importantly, regardless of whether the bend is made as a hard way bend or easy way bend the springback results are predictable.

4.2.1.7 Work Hardening Effects

Work hardening effects do not significantly affect the bend characteristics of conduit for the tighter bend radii found in lead and transition bends. This stands in stark contract to the findings of the studies performed in roll bending. The gentler bends formed in the roll bending are directly affected by small changes in material hardness. The data for effects of cold working on the lead and transition bends is presented in Figure 19 (for CS Conduit) and in Figure 20 (for PF Conduit).

4.2.1.8 Reaction Cycle Effects

(See Section 6)

4.2.1.9 Bending Force

The hydraulic pressure required to bend each sample was recorded at each loaded angle, from this data the force can be calculated. The maximum pressure required and the loaded angle at which it reached maximum pressure for each sample is as follows:

SAMPLE ID (TF)	DIE RADIUS	MAX. LOAD (PSI)	LOADED ANGLE
TF 1	7.5"	2450	110 °
TF 2	7.5"	2850	110 °
TF 3	9"	2480	110 °
TF 4	9"	2850	110 °

SAMPLE ID (PF)	DIE RADIUS	MAX. LOAD (PSI)	LOADED ANGLE
PF 1	9"	2400	110°
PF 2	7.5"	2600	110°
PF 3	6"	2650	110°
PF 10 (1)	9"	2700	110°
PF 10 (2)	7.5"	2800	110°

SAMPLE ID (CS)	DIE RADIUS	MAX. LOAD (PSI)	LOADED ANGLE
CS 1	6"	2400	110°
CS 2	6"	2450	110°
CS 3	6"	2450	110°
CS 4	7.5"	2250	110°
CS 5	7.5"	2300	110°
CS 6	9"	2200	110°
CS 7	9"	2250	70°
CS 8	7.5"	2100	110°
CS 9	7.5"	2200	110°
CS 10	7.5"	2300	110°
CS 17 (1)	9"	2400	110°
CS 17 (2)	7.5"	2550	108°

4.2.2 MATERIALS

Material variability had no discernible impact on the results of the bench bending for radii of 7.5" or larger. The variability observed in the CS lead bend repeatability testing for 6" radii may have been the manifestation of problems with variability. Sample sizes were not large enough to establish that fact.

4.2.3 RADII

The radii being formed has a direct impact on springback. Within the normal working range the relationship is linear. This is consistent with prior analysis.

4.3 Lead Bending Conclusions

B&W has established a method for predicting the springback during a lead or transition bend. The equipment, while rudimentary, performed very well. Parametric data must be developed for each conduit bend radii, but once established they may be easily applied. It has also been demonstrated that Incoloy 908 shrinks roughly 0.1% as a result of subjecting it to the base reaction heat treat cycle. The reaction cycle does not tend to remove elastic strain.

The feasibility of using a hand held hydraulic bending tool to perform lead and transition bending has been demonstrated.

5. ROLL BENDING

5.1 Roll Bending Preliminary Analysis and Research

5.1.1 B&W ALLIANCE RESEARCH CENTER (ARC) BEND RADIUS STUDY

PURPOSE

Roll bending trials of square stainless steel tubing were conducted on the Alliance Research Center (ARC) Plant Engineering Initial Pinch Type Bending Rolls. The purpose of the trial was to determine if the rolls could form a cross section with stiffness equivalent to that of the TF magnet conduit, and to develop bending parameters in support of the TPX contract. Three spacer rolls were fabricated from Carbon steel stock to adapt the rolls for bending 1" square tubing. A chord height gage was fabricated to measure the bend curvature.

MATERIAL

Type 304 square stainless steel tubing 1" by 0.120" wall was chosen to approximate the stiffness of the TF conductor. Square Carbon steel tubing, 1" x 1" x 0.065" wall, was used for tooling tryout.

EQUIPMENT

Roll Bender

The bending trials were run on the Hendley Beloit Model 4-D Initial Type Bending Rolls located in the ARC Plant Engineering Department. The roll diameters are 7".

Curvature Gage

The chord height curvature gage is shown in Figure 4. The gage measures the chord height on the inner bend radius. The magnet radii and calculated chord heights are:

<u>R</u>	<u>h</u>
41.4	0.4425
60.7	0.2997
228.7	0.0789

Because the gage bar contacts the edges of the inner surface, while the dial gage contacts the middle, the gage readings were reduced by 10 thousandths to correct for the concavity.

TECHNIQUE

The arrangement for rolling angles is shown in Figure 1. Three spacer rolls were machined to provide a roll groove 1" wide by 1/2" deep to support one-half of a 1" square cross section, Figure 2. The spacers were machined from carbon steel bar stock. The spacers were satisfactory for roll bending the carbon steel tubing (1" square x 0.065" wall). The spacer rolls were not hard enough for bending 304 stainless tubing 1" square x 0.120" wall. The stainless tube formed about a 10 thousandth deep groove in the spacers near the edges where the contact pressure was high, Figure 3. The square tube conformed to the spacer causing about a 0.010" concavity across the inner bend radius.

Bending Trials

Carbon Steel - Square Carbon steel tubing, 1" x 1" x 0.065" wall was successfully formed incrementally to the three magnet radii. See the top of Figure 5, tubes 1, 3 and 5. When the same roll setting was used to make the bend in a single pass, a much tighter bend radius was formed, tubes 2, 4 and 6 at the top of Figure 5. This result was unexpected. Having verified the operation of the rolls, testing shifted to the heavier wall thickness stainless tubing that approximates the stiffness of the magnet conductor.

Stainless Steel - Stainless Type 304 ornamental square tubing, 1" Square x 11 gage (0.120" wall) to ASTM A-554-90, was purchased for the bending trials. Three foot tube lengths were cut for the setup trials for the 41.4" bend radius.

Trial roll settings were made, and the chord height was measured at the apex of the bend. Seven bends were made. The correlation of Bend Roll to Top Roll Space with chord height is plotted in Figure 6. Grooving of the spacer rolls was noted after bending tube #3. Variability of the chord height is apparent in the graph.

Tubes 6 and 7 were run at the same roll setting, and had significantly different bend radii as pictured in Figure 7. The chord height was measured at 3" intervals. These results are given in Figure 8. For calculating the bend radius, the chord heights were reduced by 10 thousandths to compensate for the concavity of the inner bend surface. The bend radius variation is shown in Figure 9. Possible sources of the variability include: the tube material, the spacer roll grooving, roll run-out, clearance between the roll and roll shaft, and wear in the bearings and ways.

To better assess the machine variability, two 10' long tubes were bent at the same setup. Chord height measurements were made at 3" intervals along the arc. The chord height and bend radius variations, for tubes 8 and 9 are listed in Table 1 and plotted in Figures 10 and 11. Note the periodic variation of the bend radius with arc length. The average period is 20.5". This corresponds to a neutral roll diameter of 6.5". This variability is due to run-out of the three bending rolls. The chord height and bend radius measurements are summarized below:

		Standard		
		<u>Mean</u>	<u>Deviation</u>	<u>Range</u>
Chord Height	Tube 8	0.479	0.006	0.466 / 0.491

	Tube 9	0.484	0.008	0.471 / 0.498
Bend Radius	Tube 8	39.10	0.50	38.24/ 40.20
	Tube 9	38.74	0.64	37.63/ 39.78

As an overall check, the chord length and height were measured with a tape measure between the 1' and 9' arc length positions. The average bend radius was calculated as shown in Table 2. The average bend radii were 39.29" and 38.94" for tubes 8 and 9, respectively. Excellent agreement between the mean and the average radii was achieved.

The statistical data gives an indication of the machine capability. A larger sample size is required to find the standard deviation of the average bend radius.

Adjustment of the bending roll position is not precise. The roll adjustment screw is not designed to move the bending roll under load. Because of the bend radius variability, and the limitations of the roll adjustment screw, changing of the bend radius in the middle of a tube was not attempted. Further trials with the ARC bending rolls are not warranted.

RESULTS AND CONCLUSIONS

1. Testing demonstrated that the ARC Plant Engineering Initial Type Bending Rolls can bend Stainless steel tubing 1" square x 11 gage (0.120" Wall).
2. To fit the 1" square tube cross section, spacer rolls were made of Carbon steel. The spacer rolls were too soft for bending the stainless tube. Grooves were formed at the high contact pressure areas near the roll edges about 0.010" deep. A harder material is required.
3. Initially square Carbon steel tubes, 1" x 0.065" wall, were formed incrementally in several passes to determine the roll setting for the desired bend radius. A second tube was bent in one pass at this roll setting. The second tube, unexpectedly, formed to a much smaller bend radius.
4. Several Stainless tubes, 1" square by 0.120" wall, were bent in one pass to find the proper roll setting. High degrees of variability were observed in the chord height and bend radius when the machine setting was held constant. Because of the high variability of the bend radius, a double bend contour was not attempted.
5. Two additional stainless tubes 10' long were bent using the same roll settings. The bend radius had a sinusoidal variation with a frequency corresponding to a bending roll neutral diameter of 6.5". This variation is ascribed to roll run-out. The spread in chord height, 0.032", is approximately 4 standard deviations. The corresponding spread in bend radius was 2.5".
6. The high variability observed in these few tests indicates that forming the TF Magnet contour requires a roll bending machine with much greater setup precision than is found in commercial bending rolls.

Figure 1. Arrangement of Rolls

Figure 2. Spacer Roll Detail

Figure 3. Edge Grooving in Spacer Rolls

Figure 4. Chord Height Gage

Figure 5. Bend Samples

Carbon Steel 1" Sq. x 0.065" Wall Bends 1 to 6 @ Top
Stainless Steel 1" Sq. x 0.120" Wall Bends 1 to 7 @ Bottom

Figure 7. Difference in End Position between Tubes 6 and 7 Run with the Same Roll Setting (36" Length)

i := 0..6
Tube_i := i + 1

Tube _i	C _i	h _i
1	2.733	.255
2	2.497	.461
3	2.501	.450
4	2.493	.406
5	2.475	.425
6	2.450	.465
7	2.450	.605

Figure 6. Correlation of Bend Radius with Roll Setting

S_i	$H6_i$	$H7_i$
6	0.386	0.434
9	0.453	0.473
12	0.466	0.472
15	0.478	0.494
18	0.465	0.505
21	0.443	0.496
24	0.429	0.474
27	0.436	0.459
30	0.424	0.444

Figure 8. Chord Height Variation with Length for Tubes 6 and 7 (36" Length)

S_i	$R6_i$	$R7_i$
6	48.56	43.165
9	41.354	39.608
12	40.202	39.692
15	39.196	37.932
18	40.288	37.111
21	42.287	37.78
24	43.669	39.525
27	42.967	40.814
30	44.185	42.192

Figure 9. Bend Radius Variation with Length for Tubes 6 and 7 (36" Length)

Figure 10. Chord Height Variation with Length for Tubes 8 and 9 (120" Length)

Figure 10. Bend Radius Variation with Length for Tubes 8 and 9 (120" Length)

5.1.2 TF COIL WINDING TABLE MOVEMENT ANALYSIS

The second portion of the ARC winding development work was analysis of required production winding table position as a function of bend radius for the TF coil. The key issues regarding winding table movement analysis are the winding table movements, and the number of degrees of freedom required to maintain tangency of the coil with outlet of the bender.

Winding Movements - Supporting Analysis

The "D" shaped TF coil geometry is shown in Figure 12. The arc centers were calculated from the various coil radii and the included angle for each arc. The "x, y" coordinate system and magnet center are also shown in Figure 11. The conductor center is at the intersection of the x axis with the line through the common radii centers as marked by the diamond.

To maintain tangency of the coil with the bender, the conductor coil table must move in three dimensions: x and y displacement of the coil center as plotted in Figure 12, and angle of rotation about the coil center as plotted in Figure 13. Regardless of what the configuration of the bender and/or the coil table, three degrees of freedom are required. In addition, the preferred despooler design indexes vertically to maintain the conductor payoff in the plane of the winding machine. The conductor centerline through the straightening and bending rolls may cant slightly to assist in lowering the conductor from the bender onto the winding form. The tooling can be rotated about the conductor axis to remove twist imparted to the conductor during spooling.

Figure 11. Plot of TF Magnet Coil Inner Contour and Center Point

Figure 12. Winding Path of TF Magnet Coil Center (Coil Tangent to Bender Outlet)

Figure 13. Plot of Magnet Angle of Rotation (angle) vs. y Axis Coordinate of Coil Center

5.1.3 STUDY OF BENDING / WINDING ACCURACY

A third study was performed to determine the required bend radius accuracy and length measurement accuracy required to control conductor-to-conductor gaps to less than 0.010". The two key factors controlling the accuracy of the coil winding operation are:

- Bend Radius
- Arc Length.

In fitting the coil up to the form, it may be possible to adjust the bend radius. The length cannot be adjusted!

Bend Radius

For the relatively large coil bend radii, the bend radius can be adjusted slightly by springing the bend to either open or close the bend. Thus, some deviation from the nominal bend radius is tolerable, as long as the bend radius is **uniform**. While a non-uniform bend radius can be sprung, the non-uniformity will remain, and the non-uniform section will not fit-up with adjacent turns.

When coiling **inside to outside**, a slight overbend is preferred. A low tension level on the winder will spring the bend open to fit around the previous turn. Elastic springback will hold the conductor tightly to the previous inner turn. An under bend would require tension winding to hold the conductor against the preceding turn.

When coiling **outside to inside**, a slight under-bend is preferred. The bend is sprung elasticity to fit inside the previous turn. The bend then springs out and is constrained by the previous outer turn. An overbend would have to be sprung open and held in place. Elastic springback would cause the conductor to pull away from the previous outer coil leaving a gap.

In summary:

1. Bend uniformity is required.
2. Coiling inside to outside, the bend radius tolerance should be to the minus side.
3. Coiling outside to inside, the bend radius tolerance should be on the plus side.

Arc Length

The length of the conductor may change slightly during bending depending on the location of the neutral axis relative to the centerline of the conductor. The conductor will stretch if the neutral axis lies inside of the bend centerline, and shrink if the neutral axis is outside of the conductor centerline. This effect must be allowed for in the control of the winding machine. The length of the conductor cannot be changed to fit the contour form. Consequently, the length of each arc segment must be tightly controlled.

Accurate measurement of the conductor length on the outside of the bend, inside of the bend, and the conductor height can be used to estimate the bend radius and the neutral radius. The average outlet feed relative to the inlet feed determines the bend stretch or shrinkage.

To estimate the required length accuracy, an analysis was made for the 3 TF magnet bend radii. For the full arc, and for an 18" chord length, the arc to produce a specified radial gap was calculated. The construction is shown graphically in Figure 14 for a much larger radial gap.

The variation of the differences in bend radius and arc length with gap for the 41.4" bend radius 90 degree bend are shown in Figure 15. The variations are linear for a gap range from 0 to 0.020". For a 0.010" gap, the bend radius is 0.0242" oversize, and the arc length is 0.0104" short.

The results for the three conductor bend radii with a 0.010" gap are listed in Table 1 for the full bend arc and for an 18" chord length. The 0.010" gap was a product of design engineering analysis. The key items are the differences in the bend radii and the arc length between the nominal values and the values calculated for a 0.010" radial gap.

For the 41.4" radius, the full arc length must be accurate to within 0.0242" to hold the gap under 0.010". For the 18" chord length the required accuracy is 0.0029". Dividing the arc length difference by the arc length, yields a required accuracy of 0.00016 in./in. for the 41.4" radius.

For the 60.7" radius the accuracy requirement is 0.00011 in./in., and for the 228.7" radius 0.000028 in./in. The largest bend radius requires the highest accuracy.

The winding machine gauging will measure to 0.0001", which is sufficient for the tighter bend radii. The larger 228.7" bend radius may have to be fitted and held in position.

Figure 14. Gap Between Arcs with Common Chord Length

Figure 15. Difference in Bend Radius and Arc Length vs. Gap

Table 1. TF Coil Arc Length and Bend Radius Variation for a 0.010 in. Gap

(for the Full Arc and for an 18" Chord)

<u>Bend</u>	<u>Chord Length</u> inches	<u>Aim:</u>		<u>Calculated for 10mil Gap</u>		<u>Difference</u>		<u>Arc Length Accuracy for 10mil Gap</u>
		<u>Bend Radius</u> inches	<u>Arc Length</u> inches	<u>Bend Radius</u> inches	<u>Arc Length</u> inches	<u>Bend Radius</u> inches	<u>Arc Length</u> inches	in/in
Full Arc	58.5484	41.4	65.031	41.4242	65.0206	.0242	.0104	.00016
18" Chord	18		18.1449	41.8124	18.1420	.4124	.0029	.00016
Full Arc	78.7528	60.7	85.6941	60.7319	85.6847	.0319	.0093	.00011
18" Chord	18		18.0666	61.6083	18.0646	.9083	.0020	.00011
Full Arc	72.4353	228.7	72.7415	229.4852	72.7394	.7852	.0012	.0000290
18" Chord	18		18.0046	242.3715	18.0041	13.6715	.00051	.0000283

5.2 Roll Bending Machine, Fixtures, and Technique

B&W procured a Tauring three roll roll-former to perform initial roll-forming development. The unit, seen in Figure 16 with the radius gauge was modified as described herein to perform the development work.

5.2.1 ROLL BENDING MACHINE & MODIFICATIONS

Tauring 3 Roll Roll Former

The roll former was configured initially with the rolls that came with the machine (2.7 in and 5.7 in Dia.) later, an additional set of 3 rolls (3.7 in Dia.) was procured.

The roll positioning is accomplished as follows: one roll is positioned manually by means of a hand crank (ref. Figure 17). This roll is normally locked in position, set for a given radius to be formed. A second roll was positioned hydraulically to a - previously established setting for a given radius to be formed. This roll is moved initially to allow the insertion for the CICC to be formed. It is then repositioned to the established setting for a given radius. The third roll is fixed. All roll shafts are driven by a central large driving gear. Between the splined shaft for the fixed roll and the large drive gear, is an idler gear to cause the fixed roll to turn in the same direction as the moveable rolls. The hydraulically positioned roll is moved by jog buttons on an operator pedestal. An internal rotary encoder reads roll position of this roll and a reference setting is displayed on the operator pedestal indicating the roll position. This reference is used when moving this roll from the CICC insertion (open) position to the roll forming position. Also at the operator station are foot pedals

Figure 16. Tauring Roll Bender with Radius Gauge

Figure 17. Roll Configuration on Tauring 3

which allow the turning of the rolls in either direction.

Reference scales are mounted adjacent to each moveable roll. These scales are useful when developing initial machine settings for a given radius or repositioning after insertion of CICC (in conjunction with pedestal setting) for returning to an established setting.

This roll former does not allow for varying the RPM of the gear reduction i.e., it is a constant speed device. Either such a capability would have to be built into the coil winding machine or sufficient off-line development would be required to optimize the feed rate(s) for material (CICC) and radii to be formed.

This simple roll former has demonstrated that it is feasible to use roll forming to wind TPX Coils. Further refinement beyond the existing equipment would be required to smoothly transition from one radius to another not only for the TF coils but also for the CS and PF coils.

Roll Hardness Data

Hardness values shown are average of at least 9 reading spaced on 120° symmetry. Usage is the number of bendings the rolls have performed prior to the time the hardness was checked. Values are Rockwell B and C as indicated. No significant deformation of the rolls was observed during testing.

<i>Original Rolls</i>	<u>Top Face</u>	<u>O. D. Surf</u>	<u>Usage</u>
3 Small, 2.7 in. dia.	B98	B94	>75
3 Large, 5.7 in. dia.	B98	B95	>75
<i>New Rolls</i>			
3 Small, 3.7 in. dia. -	C52	C49	10

5.2.2 RADIUS GAUGE

The Radius Gage constructed by B&W allowed the on-line, as well as manual, use to measure chord heights and arc length traveled while bending CICC. A rotary encoder driven by friction between the conduit and a rubber o-ring mounted in a groove on the contact wheel measures arc length traveled. The chord height for the free state of the as-bent radius was measured by an LVDT located just down stream from the roll former.

Chord lengths can be adjusted (10 in., 15 in., 20 in.) for the desired as-bent radii. The LVDT is initialized by placing a large metal straight edge between the chord points and "zeroing" the output voltage. The data taking, sampling rates and averaging frequency can be varied to those suited for the application. The current match of rates and conduit bending results is an over sampling of radius data considering the application and need.

Software used the collected data to calculate, portray and plot the free state, as-bent radius vs. arc length. Additionally, software can calculate the as-bent included bend angle for the average radius either on-line or in manual, hand-fed operation. Further, when in the on-line mode, the feed rate in arc length inches per minute can be calculated, displayed and printed. Initial choices were made in setting up the data taking and sampling rates as well as the post processor (MS Excel). The gauge was placed in service and found to perform very well.

Some local fluctuations about the average radius were observed. These are judged to be the combined effect of mechanical fluctuations during operations as well as electronic. It was decided after some data had been gathered and examined that some electronic changes could be made at low cost. It was also recognized that further changes had some implications of invalidating the data base acquired. So, only minor changes were made, leaving the validity of the database intact but operating at somewhat less than optimum conditions. To optimize the gauge, additional experiments are needed to increase its resolution. Noise reduction is possible and is influenced by many factors. Further progress to minimize local apparent fluctuations in as-bent radius will require a better match between the electronics and the required bending documentation. After that, the mechanical effects of roll roundness and run-out, shaft/roll fit up, key and keyway fit and possibly vibration could be addressed.

Despite all the recommended modifications, the basic feasibility of using such devices while roll forming (winding) TPX coils has been established. Strategic placement of such sensors will allow assessment of the winding as it progresses so that required corrections can be made.

5.3 Roll Bending Data Summary

5.3.1 ROLL BENDING EFFECTS

5.3.1.1 Roll Bending Cold work effect

Purpose: To simulate the effect prior cold work would have on coil winding, where CICC material may be bent, straightened and rebent one or more times in order to accomplish shipment and coil winding.

Materials: CS and PF materials were used. Insufficient TF CICC was available at the time for this simulation. The CS material had been preformed at least once to about a 50 in. radius prior to shipment to B&W. A five foot arc was cut from the as-received coil for sample CS 17. The PF CICC was initially in a straight length as-received. A five foot straight length was cut for sample PF10.

Technique:

CS 17 was given successive bending and straightening cycles for a total of three radius bendings and two straightenings for this simulation, i.e., formed from the initial preform, straightened, re-formed, straightened, and re-formed. The as-received preformed radius allowed the CICC material to be started in the roll bender. No special start-up preform was required for any of the CS radius bending. Straightening consisted of resetting the machine as necessary to accomplish straightness. At least two straightening passes were required prior to both the second and third radius formings. The machine settings were returned to those used for the initial radius forming. After each forming the as-bent radius was measured using the automated radius gauge and recorded. Plots of the resultant radii against arc length are shown in Figure 19. This piece was subsequently straightened again and used as a lead bending sample with prior cold work.

Figure 19

CS Cold Work

PF-10 was similarly given cold work cycles. Unlike the CS sample, the PF sample did require a short (6" long) preform to allow it to enter the roll former. The cold working of this sample after preforming consisted of a total of three radius formings and two straightenings for this simulation. As was the case with the CS CICC the same machine settings were used for all three radius formings. (These settings were in fact the same settings used for all six radius formings, i.e. The same settings were used for both CS and PF CICC.) As-bent radius was gauged and recorded. Plots of the resultant radii against arc length are shown in Figure 20. This piece was subsequently straightened again and used as a lead bending sample with prior cold work.

Figure 20

PF Cold Work

Discussion:

The repositioning (resetting the machine) of the entrance roll to the same configuration for all radius formings is controlled by a rotary encoder built into the hydraulic roll positioning system. It repositions the entrance roll within 0.004 in. of a previous setting. The rotary encoder causes a reference number to be displayed on the operator floor pedestal which can be repeated by means of jog buttons. The hydraulic oil pump is off after positioning the entrance roll and some movement of this roll had been detected (approx. 0.030 in.) during previous roll bending. However this movement does not account for 22% to 32% radius changes exhibited by the subsequent bends of the PF and CS CICC since the same amount of movement would have occurred for each bending.

It should be noted that only one of the three rolls was moved to accomplish the forming/straightening cycles. A second roll which can be moved by a hand crank was locked in place for the entire simulation. The third roll was not moveable.

The radius gauge has been shown to repeat within 0.2% on successive readings of a given as bent sample radius. It was demonstrated that mechanical considerations (roll runout under load, fit of roll to shaft, vibration, etc.) do contribute to periodic radius variation. But, regarding the work hardening and resultant increase in springback, the simulation has shown the effect is dependent on the amount of cold work prior to bending. This simulation addressed the range of the smaller radii found in the TPX coils. The larger, more gentle radii could be expected to exhibit smaller responses (spring back). Consistent successful roll forming to TPX design radii is feasible if the prior strain history of the conductor is consistent and characterized before use.

Conclusions:

1. The response of CICC to roll forming is dependent on the amount of cold work induced by fabrication and forming prior to coil winding. If one bend-straighten-bend cycle is all that's required of the CICC than a change in response of up to 32% may be anticipated for CS CICC. Similarly, a change in response for PF 6/7 CICC of up to 22% may be anticipated.
2. To allow successful coil winding using these materials, characterization of the CICC material is required to formulate a base of expectation for the bending response to a given set of CICC processing conditions. Once CICC process norms are established and characterization has established such a base, predictable coil winding should be possible. Local corrections to as formed CICC should be anticipated and access allowed by the design of the winding machine. As a minimum short lengths (25 - 50 ft.) should be subjected to the intended amount of bending prior to committing a production spool of CICC to coil winding. Leading and trailing samples evaluated at the supplier or at the winding shop or both should be planned for initially until a base of information can show that such characterization is not required.

5.3.1.2 Roll Bending Repeatability

Purpose: To evaluate repeatability of the response to roll bending of multiple samples of CS and PF CICC.

Materials: Five 10 ft. lengths of CS CICC were cut from the 50 in. radius preformed coil for mockups CS 18, 19, 20, 21 and 22. Five 10 ft. lengths of PF CICC were cut from available longer straight lengths for mockups PF 5, 6, 7, 8 and 9.

Technique: Prior to performing the roll bending of the CS and PF CICC materials, it had been established that some changes to roll diameter and height were desirable. The roll bender was reconfigured with harder, smaller rolls (See Equipment discussion.). Also, the roll height was reduced, allowing the guides to better "capture" the CICC cross section as the bending progressed. The shorter rolls reduced the amount of keystoneing when rolling TF CICC. The opening between the guides was reduced from 1.125 to 0.900 in. The roll diameter was adjusted to capture about half of the conductor width in the plane of the bend. Clearance of the fit of the roll to shaft was reduced from 0.0050 to 0.0015 in. Mockups PF 5 and PF 6 were used to prepare for the repeatability run. PF 5 served a dual role as it was also used to demonstrate the radius gauge for Westinghouse visitors

Preparations for Mockups CS 18 and 19 were similar.

Figure 21

Figure 22

Figure 23

The remaining CS CICC samples (CS 20, 21, and 22) were used as repeatability samples after the roll bender reconfiguration and radius gauge checkout. The as-received radius and the after bend radius of each of these three samples was measured. Range and periodicity were documented. These data were subsequently plotted along with the as bent radius for comparison purposes.

These plot follow (See Figure 21, Figure 22, and Figure 23). Pre- and post-bending cross section dimensions were taken. Post-bending hardness values were also taken.

The remaining PF samples (PF 7, 8, and 9) were also used as repeatability samples after roll bender reconfiguration and radius gauge checkout. These plot follow (See Figure 24, Figure 25, and Figure 26). Pre- and post-bending cross section dimensions were taken. Post-bending hardness values were taken as a result of anomalous bending results.

Results and Conclusions: The roll bender reconfiguration had desirable effects. The as-bent radius variation was reduced from as much as 3.5 inches in a given sample, to 1.2 in. for CS CICC. Like wise, for the PF material, a radius range reduction from 1.9 in to 0.6 in

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was achieved, excluding one sample PF 8 judged to be non-representative. The range on average radius among the three samples also improved (reduced). For CS CICC, the prior range among samples was reduced from 7.8 in. to 0.3 in.

Two of the CS samples (CS 20 and 22) behaved as expected. However, CS 21 had a pre-formed radius variation in a 30 in arc length of 6.5 in. above the average for the as-received material. After roll bending, this radius variation was reduced to 2.0 in. above average. An initial set of hardness readings revealed that CS 21 exhibited values significantly different from CS 20 and CS 22, indicating that the radius variation resulted from differences in hardness of the starting material.

	<u>At 10 in.</u>	<u>At 30 in.</u>	<u>At 60 in.</u>
CS 20	B 97.0	B 96.0	B 96.3
CS 22	B 96.0	B 99.0	B 97.3
CS 21	B 86.5	C 24.0	C 23.5

Figure 24

Figure 25

The above values suggest a different strain history for CS 21 than that of CS 20 and 22. No tubing butt weld is associated with the radius excursion shown by CS 22. Further investigation involving a more detailed hardness study of CS 21, showed the hardness values on either side of the 30 inch arc length, with the above average radius, averaged a Rockwell hardness of B 98. The hardness values at the center of the 30 in. arc length (about 25 in. from the lead end) are C 26. The values on either side of this center drop off forming a profile that matches the average radius profile for the 30 in. of arc length.

The inability to identify the source of variability for this phenomenon validates the need to characterize the incoming CICC by working with CICC suppliers and doing in-house work as necessary to ascertain the response to bending prior to coil winding.

The initial hardness values for the PF CICC were:

	At 10 Inches	At 30 Inches	At 60 Inches
PF 7	C 27	C 26	C27
PF 8	C 25	C 27	C 26
PF 9	C 26	C 27	C 27

Figure 26

The values in the table above suggest similar strain histories for the three samples. PF 8 exhibited a somewhat different radius profile than PF 7 and 9. PF 8 produced a gradually increasing average radius over its entire length, while PF 7 and 9 exhibited a periodic variation around the average similar to CS 20 and 22. A review of all of the available information has not suggested an assignable cause for the atypical bending response of PF 8.

The cross sectional changes resulting from the roll bending were as

expected. For the CS samples in the plane of the bend the cross section was reduced by 0.008 in. Perpendicular to plane of the bend the cross section increased 0.004 in. The comparable values for the PF CICC were - 0.005 in. and + 0.002 in, respectively

5.3.1.3 . Roll Bending Twist, Bulging, and Keystoning

- Purposes:**
1. Evaluate keystoning, bulging and twist as a result of roll bending.
 2. Compare keystoning and bulging between two different roll sets

Materials: Dummy TF CICC was used. Mockup TF-6 was cut from straight lengths. A second piece furnished earlier by LLNL and bent with the initial roll set was used for comparison mockup. CICC processing of the two TF samples is believed to be identical.

Technique: The roll former was used to bend both samples. Sufficient dimensional measurements were made to document keystoning and bulging on both mockups and twist on the more recent TF-6 mockup. The average values of individual readings (cross sectional dimensions) are shown in Figure 22. The newer set of rolls were intended to keystoning by means of tighter fit on the TF CICC. The prior set had an opening of 11/8 in. On the 0.890 dimension of the TF CICC. The correspond opening for the new rolls is 0.900 + .001-.000 in.

- Conclusions:**
1. Keystoning exhibited by mockup TF-6 was 0.019 in. (0.9163 - 0.8973 in.), using the tighter rolls. For the original rolls, keystoning exhibited was 0.030 in. (.9453-.9153 in.). The tighter rolls reduced keystoning by 0.021 in.
 2. The original rolls created a 0.0074 bulging of the nom. 0.890 dimension. The corresponding effect with the new rolls was 0.002 in. Concavity. The tighter rolls reduced bulging by approximately 0.007 in.
 3. The maximum twist at any inspection station (of 9) prior to bending TF-6 was 0.047 in. The maximum post bending twist was 0.032 in. These values were all in the same direction and are not cumulative. The average values of twist at any cross section before and after were 0.0188 in. And 0.0148 in. respectively. The tighter rolls has a detwisting effect.
 4. Tighter fitting rolls do reduce keystoning and bulging. It is also possible that tighter fit contributes to twist control.

TF CICC CROSS SECTION

Figure 27. CS As-Received vs. Post-Forming Radii

5.3.1.4 Weld Seam Location Effect on Roll Bending

Mockup CS 15 had the weld seam 90° to the bend plane. It was successfully bent and data acquired. However, no CS material was available with the weld seam in the plane of the bend. An attempt was made to overcome this difficulty by straightening mockup CS 16, and then roll forming it. But, the additional cold work from the straightening makes CS 16 of questionable value in a seam orientation examination. To properly evaluate weld seam orientation otherwise similar samples differing only by weld seam orientation must be roll formed and the results compared.

It is expected that the as bent radius for CICC (with the weld plane 90 deg. from the from the bend plane) will be larger than that for CICC with the weld seam in the bend plane. The CICC with the weld seam 90 deg. to the bend plane will spring back further resulting in a larger as bent radius. such an expectation is supported by the result of lead bending of mockups CS 8 and 9. However, such was not he case with CS 15 and 16, It is believed that the additional straightening of CS 16 caused additional spring back resulting in its as bent radius being greater than that for CS 15. Never the less, shown below are the as-bent radii for these two mock ups of CS CICC.

CS 15	Avg. as bent radius:	24.3 in.
CS 16	Avg. as bent radius:	24.7 in.

Data from CS 15 was useful as a part of the keystoneing examination.

6. REACTION EFFECTS

The reaction effects study focused on the impact reaction would have on the conduit's metallurgical properties. This study was required to provide basic data regarding shrinkage and distortion of a coil and the leads. Other issues such as the shrinkage of the simulated copper conductor emerged as an additional benefit of the effort.

6.1 Reaction Fixture, Furnace, and Technique

TF 58% and 50% Scale TF Coil Turns Mockups

Purpose: To examine distortions of the TF Coil turns resulting from exposure to a simulated reaction heat treat cycle

Material: Empty TF, I-908 conduit was used. The conduit was Inco seamless extruded annealed tubing, cold formed at Phelps-Dodge. It was furnished in straight lengths to B&W by Everson Electric Co.

Technique: Straight lengths were butt welded together to assure sufficient length of conduit to complete one turn of the "D." Using a compression bench bender the conduit was incrementally formed to create a single turn each of a 58% and 50% scale mock-up. At the completion of the bending, a butt weld was made at the center of the straight section of each mockup. A 0.125" air bleed hole was drilled in face of each mockup near its final center line butt weld. The mocks were dimensionally inspected. Also, at the completion of these mocks as a part of the documentation neat line-tracings were made to be used as part of the post-heat treat examination. Upon arrival at the heat treat vendor both mockups were placed in a horizontal position on a special heat treat rack. The 50% scale mockup was loosely wired to the rack with stainless steel wire, so it was unrestrained during the thermal cycle. The 58% scale mockup was positioned horizontally on the same rack concentric with the smaller mockup.

This mockup was held using some restraining clips welded to the rack. These clips constrained the mockups in the vertical. Additionally, the clips were sized and positioned to allow for thermal expansion and contraction in both dimensions in the horizontal plane. The size and placement of the clips took into account of the

**Figure 1. Data Values
Schematic for 1/2 Scale Mock-
up a TF Turn**

differential between the thermal expansions of the carbon steel rack and the Incoloy 908 conduit.

Thermal Cycle - Wall Colmonoy

The heat treat rack was blasted, wiped down, and baked out prior to use. The various mockups were attached to the rack after bake out. The loaded rack was placed in a large circular vacuum furnace. After out-gassing, the temperature was ramped up to 650°C, and held for 50 hr., followed by a cool down which included the use of argon to facilitate cooling. The furnace was opened at 200°C the rack and mockups were returned to B&W for post heat treat inspection.

Note: Other "CS" mockups (a spiral, a flat coil as well as lead bend samples) were included in the same run. These mockups contained copper strands that were not oxygen free copper. Further, the cable had been lubricated with Mobil 1 for drawing into the conduit. As a result, there was some discoloration of the mock-up.

Dimension	50% scale					58% Scale			
	Before	After	Change			Before	After	Change	
	in.	in.	in.	%		in	in	in.	%
Inside X	52.7	52.63	-0.1	0.19		60.4	60.3	-0.1	0.17
Inside Y	87.31	87.3				101.1	101.1		
R ₁ Avg.	21.5	21.6	+0.1	.05		23.4	22.8	-0.6	2.6
R ₂ Avg.	33.0	34.1	+1.1	3.3		35.3	35.6	+0.3	0.8
R ₃ Avg.	22.1	22.3	+0.2	0.9		24.1	23.7	-0.4	1.5
R ₄ Avg.	31.6	32.2	+0.6	1.9		37.0	36.7	-0.3	0.8
R ₅ Avg.	158.2	161.5	+3.3	2.1		143.5	141.2	-2.3	1.6
Outside Circumference	240.6	240.4	-0.2	.08		276.3 ⁽¹⁾	276.7	+0.4	0.1

(1) "Before" suspect on the 58% mockup.

Discussion: The as-built dimensions achieved on the mock-up were a satisfactory scaling of turns in a TF coil. The presence of Mobil 1 caused some black residue at the exposed ends of the CS spiral mockups. The coloration of the mockups was light gunmetal blue in a barber pole pattern fading to darker shade on the "D" scaled mockups. The likelihood a SAGBO is judged to be minimal based on hardness data. This run does establish that the heat treatment of the TF coils does not distort the conduit significantly. Due to the limited time available, no metallographic analysis was performed.

Conclusions:

The thermal distortions exhibited are not unexpected. The magnitudes are within the range of the measuring capability of the equipment available (tape measures, scales and the radius

gage). Little or no distortions were detected when replacing the "D" mock ups on their pre-heat treat tracings.

CICC Reaction Effects CS Coils

Purpose: To evaluate the effects of the reaction heat treatments on wound coils.

Materials: CS-CICC lengths were cut from the 50 in. radius pre-formed coil.

Technique: One length was roll formed into a flat coil of 2 3/4 turns. The coil (mockup CS-13) was placed on a heat treat rack in a horizontal position and the end of the inner turn was welded to the rack. The end of the outer turn was left unattached and free to move in response to the heating and cooling of the reaction heat treat cycle. Clips were welded on 90° symmetry which loosely confined the coil in the horizontal plane. The clips were positioned so that the differential thermal expansions of the rack and the coil would allow the coil freedom in the radial as well as the circumferential directions. Dimensional measurements were taken before and after the heat treat cycle. Radial scribed lines were made turn-to-turn for post heat treatment examination of circumferential, relative turn-to-turn shift. The outside diameter of this coil was 44 in. prior to heat treatment.

The sample placement was as shown in

Figure 2 and

Figure 3 for both the coil mockups.

Similarly, a second length was cut and roll formed into a coil with 2 1/4 turns in the bottom layer (mockups CS-14). A 1/4 turn ramp up to the top layer led to 1 1/4 turns in the top layer. The coil was laid on the rack in a horizontal position. It was likewise constrained by welding the end of the inner turn to the rack. The coil was thus allowed freedom in the radial, as well as circumferential directions. Radial scribed lines were used to document the circumferential shift resulting from the thermal treatment. Pre and post heat treat dimensional inspections were made. The preheat outside diameter of this spiraled coil was 60-3/4 in.

A straight length of conduit was also included as a hardness/length change control sample.

The rack was of welded construction using steel beams. The rack was blasted, wiped down and baked prior to sample placement.

The thermal treatment was performed in a large circular vacuum furnace. Thermal cycle following out-gassing consisted of ramping up to 650°C, holding for 50 hrs. and ramping down to 200°C at which temperature the furnace was opened.

Argon gas was used to facilitate the cool down. The vacuum attained was 10^{-4} torr. Six thermocouples sensed the mock up temperatures. Their placement is shown in the illustrations.

6.2 Reaction Data Effects Summary

Note: All of the mock-ups used in this program were made from empty conduit and dummy conductors, so none of them contained superconducting material. Consequently, an abbreviated reaction cycle could be used to check the reaction effects on the conduit.

The cycle used the same temperature profile, (extremes and levels) but shortened the soak times and eliminated some of the intermediate soak times. The lengthy 200 hour soak time in the full length cycle is required for the chemical reaction to form the superconductor. The length of the main soak time was reduced from 200 hours to 50 hours. These mock-ups have very low mass and came up to temperature very fast. This temperature and soak time was within the heat treat cycle recommended by Inco.

6.2.1 LEADING BEND CHANGES

Purpose: To evaluate the effects of the reaction heat treatments on lead and transition bends.

Materials: CS dummy conductor lengths were cut, as needed, from the 50 in. radius pre-formed coil. TF empty conduit was cut as needed from the GFE straight lengths provided. PF 6/7 dummy conductor was cut from the GFE straight lengths as needed.

Technique: To determine the effect of the reaction cycle on prior bent conduit we cycled 12 of the bent conduit mock-ups through the reaction process. Angles, dimensions, hardness, and cross sections were recorded before and after the reaction cycle.

Mock-ups CS4, CS5, CS6, CS7, TF1, TF2, TF3 and TF4 were lead style bends. These mock-ups were punch marked near each end and the distance between punch marks recorded. Templates were drawn of each of the mock-ups and the "before shape" compared to the "after shape".

Mock-ups CS17 and PF10 each had 2 bends (one 7.5" die and one 9" die) on each conduit. They were punch marked across each of the two bends.

Results: The as-formed radii data and the after-reaction dimensional data are contained in Figure 4.

LEAD BENDING DIMENSIONAL DATA CHANGES AS A RESULT OF REACTION

Sample ID	Die Radius	(R) Measured Radius	(A) Before Reaction	(A) After Reaction	(D) Before Reaction	(D) After Reaction	Changes
CS4	7.5"	7.9"	89°	89.6°	28"	27.75"	-.25"
CS5	7.5"	7.8"	90.3°	89.8°	28"	28"	0
CS6	9.0"	8.9"	89.5°	92.4°	28.125"	28.25"	+.125"
CS7	9.0"	8.8"	92°	93.9°	28.312"	28.5"	+.188"
TF1	7.5"	7.2"	90°	92.5°	27.375"	27.562"	+.188"
TF2	7.5"	8.0"	90.5°	90.4°	27.375"	27.562"	+.188"
TF3	9.0"	9.6"	91°	92°	28.187"	28.187"	0
TF4	9.0"	9.8"	88.5°	90.1°	28.062"	28.062"	0
CS17 (1)	7.5"	7.4"	101°	100.1°	24.187"	24.25"	+.063"
CS17 (2)	9.0"	9"	90.8°	91.5°	24.125"	24.125"	0
PF10 (1)	7.5"	6.6"	91.5°	92.4°	23.25"	23.5"	+.25"
PF10 (2)	9.0"	9.1"	90.4°	92.6°	24.312"	24.625"	+.312

Figure 4. Lead Bending Dimensional Data Changes as a Result of Reaction

NOTE: Refer to Figure 5 and Figure 6 for the specific locations of the dimensions given in this table.

Figure 5. CS 4 thru TF 4 Reference

Figure 6. CS 17 (1) thru PF 10 (2) Reference

Conclusions:

1. On CS conduit the (D) dimension change was not large but was significant and variable in magnitude and direction. The angle change varied from -0.5° to $+2.9^\circ$. The TF conduit change was small and consistent on the 7.5" die mock-ups. When the 9" die was used there were no changes in the (D) dimension. On TF the angle change was consistently an increase and varied from $.1^\circ$ to 2.5° . The data seems to indicate a slight relaxation of the as-bent leads results from reaction and must be compensated for by overbending the leads roughly 1° .
2. There was no difference in the dimensional change "easy way" vs. "hard way" of TF conduit indicating no preferential relaxation results from direction of the bend.

CICC Reaction Effects Impact Upon Pre-Strained Lead Bends

Purpose: To determine the effect of the reaction cycle on protruding leads and their bend angles, and if elastic strain existed in them during the cycle. To evaluate the effects of the reaction heat treatments on these lead and transition bends.

Materials: CS-CICC lengths were cut from the 50 in. radius pre-formed coil.

Technique: These mock-ups had a 90° angle with one leg short and the other relatively long (See Figure 7). This is similar to the geometry of the leads out of the central solenoid coils.

Sample CS 24 - The angle was sprung open 3° and a length of 908 conduit was welded from end to end as a brace.

Sample CS 25 - The angle was sprung closed 3° and a length of 908 conduit welded from end to end as a brace.

CS 24 Strained (+3° before welding) Refer to Figure 7

Status	(R) Radius	(A) Angle	(B) Length	(C) Length	(D) Strut	Hardness
As Bent	7.5" die used	90.2°	*	*	*	*
Pre-Reaction (strained)	7.3"	92.5°	*	*	*	C23
Post Reaction (strained)	7.6"	92.5°	15.562"	35.937"	39.125"	C41
Post Reaction (unstrained)	7.5"	90.2°	15.75"	35.937"	38.937"	*
Δ Length	*	*	-.188"	0	-.188"	*
Δ Gap	*	*	*	*	-.322"	*
Δ Angle	*	0	*	*	*	*

* Not Applicable

CS 25 Strained (-3° before welding) Refer to Figure 7

Status	(R) Radius	(A) Angle	(B) Length	(C) Length	(D) Strut	Hardness
As Bent	7.5" die used	90.5°	*	*	*	*
Pre-Reaction (strained)	7.4"	88°	*	*	*	C23
Post Reaction (strained)	7.2"	88°	16.125"	36.625"	38.875"	C41
Post Reaction (unstrained)	7.2"	89.8°	15.812"	36.562"	39.188"	*
Δ Length	*	*	-.313	-.063	+.313	
Δ Gap	*	*	*	*	+.198	
Δ Angle	*	-.7	*	*	*	

* Not Applicable

Figure 7. CS 24 and CS 25 Data Reference

Notes:

1. The included angle was measured by a protractor, with the mock-ups in the bending fixture. We also measured the angles with a CMM, but these readings are not as accurate because the sides of the angle are not straight at the point referenced by the CMM. In the bending fixture the reference is made at the points of constraint during the bending operation, the CMM bed is not large enough to reach the constraint points.
2. CS 24- The reduction in the length of the (D) dimension was measured by, first, cutting a slug out of the brace. Next the measurement of the resulting gap was subtracted from the sum of the slug width and two saw cuts "2(.038")"
3. CS 25- The increase in the length of the (D) dimension was measured by cutting the brace, then one saw cut (.038") was subtracted from the measurement of the resulting gap.
4. The increase in the (D) dimension was determined two ways. One was by measuring the (D) dimension directly and the other by measuring the gap after the brace was cut.
5. On all of the CS mock-ups the copper was sucked in on both ends during the reaction process. This did not appear to be the case with the TF mock-ups.

Conclusions:

The angle did not change when the elastic strain was trying to reduce the angle but changed 0.7° when the elastic strain was trying to increase the angle. The two data points do not provide sufficient statistical information to infer a difference between compressive and tensile elastic stress relaxation as a result of reaction under load. It can be inferred that if any creep is experienced tending to relax the strain it is slight and should be ignored until further contrary information is available.

CICC Reaction Effects Control Samples

Purpose: To provide an unbent control sample to examine the hardness and twist changes due to the reaction heat treatment of dummy Incoloy 908 TF CICC. A piece of PF stainless steel (SS 316) conduit was also included to provide data to evaluate using stainless steel in the production reaction fixture.

Materials: One piece of TF empty conduit 32 inches long was cut from the material provided by LLNL. The tubing was Incoloy seamless, extruded, annealed and pickled empty conduit. A piece of PF stainless steel (SS 316) conduit was cut from the material provided by Westinghouse and straightened was used as an elongation/shrinkage control sample.

Technique: The technique used is as follows:

1. Vacuum Heat Treatment: Upon attaining vacuum, the temperature was ramped up to 650°C and held for 50 hours. Then the temperature was gradually decreased to 200°C, using argon to facilitate cooling.
2. A 32" long piece of CICC was hardness tested before and after the simulated reaction cycle. Hardness readings were taken on three faces of the sample at three stations down the length of the sample.

TF Sample (Hardness Values)

Face	Station					
	Serial Number End		Mid-Length		Opposite End	
	Pre-cycle	Post-cycle	Pre-cycle	Post-cycle	Pre-cycle	Post-cycle
Inside	B97	C41	B96	C42	B98	C40
Top	B98	C43	B98	C43	B100	C45
Outside	B98	C43	B98	C43	B98	C44
Average	B97.3	C41.3	B97.3	C42.7	B98.7	C43

Notes:

1. Hardness values reported at each site are the average of at least 3 readings.
2. Hardness of B100 is approximately equivalent to C23. A precise comparison can not be made between these hardness scales. Different indenters and loads are used for each of these two scales.
3. Length data was taken before and after reaction heat treatment from arrival piece

TF-002.	Before length	31.937
	After length:	31.906
	Change:	-.031", (-.1%)

4. The twist was measured at .012" before reaction and .003" after reaction. This one sample showed a tendency to straighten during reaction.

Conclusions:

1. The reported hardness values are those expected for the Incoloy 908 material conditions. Substantial increase in hardness result from subjection of Incoloy 908 to the base reaction heat treatment..
2. The CICC shrinkage of .1% is within the expected range of shrinkage. It is feasible to design for such an amount of shrinkage.
3. Reaction heat treatment does not appear to significantly affect twist indications.

PF Control Sample (Hardness Values)

Face	Station					
	Serial Number End		Mid-Length		Opposite End	
	Pre-cycle	Post-cycle	Pre-cycle	Post-cycle	Pre-cycle	Post-cycle
Inside	C27	C26	C25	C29	C24	C27
Top	C28	C28	C27	C27	C24	C26
Outside	C26	C26	C27	C28	C22	C28
Average	C27	C26.7	C26.3	C28	C23.3	C27

Notes:

1. This sample was made from SS 316, the conduit that PF 6/7 coils will utilize; which will not be subjected to the reaction cycle. We included for tooling and fixture design information
2. Twist was measured at (.005") before reaction and (.005") after reaction. There was no change.

Conclusion:

1. No change in hardness or twist were observed and this is consistent with expectations.

6.2.2 ROLL BENDING CHANGES

The material used and the furnace set-up for the roll-bending reaction effects effort are described in Section 6.1

Results:

Reaction heat treatment of the roll-formed CS coils tended shrink them. This shrinkage serves to provide benefit to coils by reducing turn to turn gaps resulting from local anomalies in the radii. The shrinkage in terms of the overall coil length bears closer examination in Phase II.

6.2.2.1 Diameter Changes

The flat coil's (CS-13) outside diameter did not change as a result heat treat. The spiral coil post heat treat outside diameter decreased 1/2 in. from 60 3/4 in. to 60 1/4 in. or 0.8%.

6.2.2.2 Relative Coil Turn Shift

: (Using radial scribed lines turn-to-turn shift was measured.) For the flat coil the average shift between the inner and mid turns was 0.120 in. or .09%. Between the mid and outer turn, the shift was 0.060 in. or 0.13%. All these shifts occurred in the same direction, tending to tighten the coil towards the end of the inner turn which was welded to the rack.

The relative shift for the ramped coil was .250 in. or 0.13%. Again, the shift was in a coil tightening direction toward the end of the inner coil which was welded to the rack.

The 31-15/16 in long control sample shortened by 1/32 in. or just under 0.1 % (0.097 %).

6.2.2.3 Radial Gap Closure

For the flat coil (CS-13), two pre-heat treat banana shaped gaps were documented. These radial gaps were 3/16 in. and 5/16. The post heat treat measurements indicated these gaps closed to 0.031 and 0.063 in. respectively. For the spiral coil no such gaps were documented. No equivalent sized gaps were observed in the spiral coil..

6.2.2.4 Copper Strand Movement

In the case of both coils (CS-13 and CS-14), the ends of the copper strands receded into the conduit. For the flat coil 9 (CS 13), the copper receded into the conduit at the fixed end 0.060 in. For the free end the copper receded 0.080 in. The comparable data for the spiraled coil are 0.130 in. and 0.190 in. respectively.

6.2.2.5 Conduit Hardness

The hardness change for the reaction run control sample was from an average pre heat treat value of 97.8 Rockwell B to a post heat treat value of 42.3 Rockwell C which is consistent with prior experimental data.

6.2.2.6 Twist

Time did not allow mockup TF 5 to be roll formed and included in the reaction heat treatment with the other mockups. This mockup is in an unbent condition and available for further study. However, twist measurements were made on the as received coil, the flat coil (CS 13) and the spiraled coil (CS 14). The latter two coils did experience the heat treatment. The as received coil provided a sample of CS CICC which did not experience the heat treatment or roll forming other than that necessary for coiling for shipment.

Materials: The remainder of the as-received 100 in. diameter pre-formed coil not used for other CS mockups provided a before heat treatment sample of CS CICC for twist assessment.

Secondly, the flat 2 3/4 turn coil (CS 13) which did experience the heat treatment provided a post heat treatment sample for twist assessment. Thirdly, the spiraled 2 1/4 turn coil provided another coil that experienced the heat treat cycle and provided another post heat treatment sample for twist assessment.

Technique: Local twist measurements were made on the three samples available to gain insight into the combined effects of roll forming and heat treatment on CICC twist. These measurements were taken on 90 deg. stations using a straight edge and feeler gauge to determine the direction of twist of the local cross section at each inspection station. The convention adopted was that positive twist existed if the cross section is twisted inward toward the coil center. Negative twist occurred when the local cross section twisted away from the coil center. The bottom turn of the as received coil was examined. The inner turn and the outer turn of CS 13 were examined. The bottom inner and outer turns of CS 14 were examined.

Results:

Mock-Up	Station	Inside Turn (in.)	Outside turn (in.)
As-received (1)	1	+ 0.005	+ 0.005
	2	+ 0.003	+ 0.003
	3	+ 0.007	+ 0.005
	4	+ 0.007	+ 0.007
CS 13 (flat) (2)	Leg A	+ 0.003	- 0.007
	Leg B	0	0
	Leg C	- 0.006	- 0.006
	Leg D	+ 0.005	0
CS 14 (spiraled) (3)	Leg A	0	0
	Leg B	0	- 0.008
	Leg C	- 0.006	- 0.006
	Leg D	- 0.006	- 0.008

- (1) These readings were on the ID and OD surfaces of the same (bottom) turn.
- (2) These readings were on the ID surface of the inner turn and the OD surface of the outer turn. The legs are those of the heat treat rack on which the coil rested during the heat treatment.
- (3) These readings were on the ID surface of the bottom inner turn and the OD surface of the bottom outer turn.

Discussion: The direction of twist indicated by the above data are valid, but the amount is not as reliable due to the measurement technique. No large reference surface allowed station-to-station comparison. However, some inferences can be made. The bottom turn of the as received coil seems to be twisted inward consistently toward the coil center line. The inner turn of CS 13 (flat 2 3/4 turn coil) went from an inward twist to an outward condition in 180 deg. and back to an inward condition in another 180 deg. The outer turn similarly had a twist change periodicity of about 180 deg. but it is 90 deg. out of phase with the inner turn. The bottom inner turn of CS 14 twisted outward in 180 deg. and did not rotate back in 180 deg. The outer bottom turn twisted outward in 90 deg. and also did not return to an inward twist.

Conclusions:

Some inferences can be drawn from the above and similar results would probably occur if all the conditions such as prior cold work, roll bending machine settings were similar and the constraint during heat treatment were similar. It must be remembered that CS 13 and 14 were virtually unrestrained to observe the tendencies of movement as a result of heat treatment. Restraint would be present when heat treating a coil.

- The combined effect of roll forming and heat treatment may change the direction of twist within a given turn.
- The direction of twist resulting from roll forming and heat treatment within a given turn may be inward or outward but more likely it would be outward.
- The twist in a given turn as result of roll forming and heat treatment may have a periodicity of 180 deg. and such periodicity may be 90 deg. out of phase between turns in a given coil.
- Further work is required to establish the frequency of the above observations. The uncertainty left by these observations has implications for the winding pack envelop as well as turn-to-turn insulation and turn-to-turn spacing.

7. APPENDIXES

7.1 Bending Development Plan

SDRL-37 B Bending Development Replan

LEAD & TRANSITION BENDING (on Bench Bender)	NO OF M/Us	LENGTH /CONDUIT	ROLL BENDING STUDIES	NO OF M/Us	LENGTH / CONDUIT
Reaction Effects			Reaction Effects		
TF 7.5"R (2), 9"R (2) -	4	N/A*	TF - 60% scale-unconstrained	1	30' TF or CS
CS 7.5"R (2), 9"R (2)	4	N/A*	TF - 60% scale-constrained	1	30' TF or CS
			TF - Twist	1	5' TF
			CS - Spiral Ramp Transition - Elastic Range + Setup	1	60' + 10' CS
General Bench Bending Trials			General Roll Bending Trials		
Springback - CS 6"(3), 7.5"(2), 9"(2) R	7	36" ea CS	Weld Seam Orientation (Twist,etc.)	1	10' CS
- TF 9" R 1 easy, 1 hard way	2	36" ea TF	Keystoning/Bulging, Twist - TF	1	10' TF
			CS	1	10' CS
			PF6/7	- 1	10' PF
- TF 7.5" R 1 easy, 1 hard way	2	36" ea TF	Process Repeatability - CS	5	10' ea
			PF6/7	5	
- PF-6/7 6"(1), 7.5"(1),9"(1) R	3	36" ea PF	Cold Working - CS	1	72" CS
			- PF6/7	1	72" PF
Weld Seam Orientation 7.5" R	3	36" ea CS			
Cold Working&Keystoning-CS	1	N/A*			
PF6/7	1	N/A*			

* Use Remnants From Other Experiments

SUMMARY DESCRIPTION OF TPX BENDING MOCK-UPS

Bench Bending Springback Mockups

Mock-up List

Central Solenoid Simulated Conductor

Formed radius using 6" Radius die, M/U CS-1, -2, -3

Formed radius using 7.5" Radius die, M/U CS-4, -5

Formed radius using 9" Radius die, M/U CS-6, -7

TF Simulated Conductor

Formed radius using 7.5" Radius die, Easy Way, M/U TF-1

Formed radius using 7.5" Radius die, Hard Way, M/U TF-2

Formed radius using 9" Radius die, Easy Way, M/U TF-3

Formed radius using 9" Radius die, Hard Way, M/U TF-4

PF Simulated Conductor

Formed radius using 6" Radius die, PF-1

Formed radius using 7.5" Radius die, PF-2

Formed radius using 9" Radius die, PF-3

Method

The bench bending springback trials will be performed using the bench bending fixture. (ref. Figure 8). Before bending the cross section profile will be measure at three points, 1" from each ends and at the middle of the sample. Figure 9 shows the cross section profile data recorded at each data point for CS and PF. The hardness of the conduit samples will be measured. For each of the die radii of 6", 7.5", and 9" the operator will bend the conduit until an included angle of 150° is achieved on the fixture. Pressure will be released and the relaxed

conduit's bend radius measured to determine the relaxed-state included angle and amount of springback. The sample is then bent to form an included angle of 130°. Pressure is again released. The radius profile is measured and recorded. . The sample is then bent to form an included angle of 110°. Pressure is again released and the conduit allowed to spring back. The radius profile is again measured and recorded. . The sample is then bent for the final test to form an included angle of 90°. Pressure is again released. The radius profile will measured the same way as before. The inspector will measure the cross section profile at each of three points on the conduit, the centerline of the bend and 1" on either side of the edge of the bending radius die. (Refer to Figure 8 for an illustration of these three locations)

For the TF bends both "hard" and "easy" way bends will be performed. The minimum radius employed in the current TF magnet design for conduit bending is 7.5", so that is the minimum radius bend attempted. For TF conduit, side 1 will be the side with the long side with the weld seam.

Mock-ups M/U CS-4, -5, -6, -7 and M/U TF-1, -2, -3, -4 are further tested in the Lead & Transition Bending Reaction Effects program (see below)

Bench Bending Weld Seam Orientation Mock-ups

Figure 8. BENCH BENDING FIXTURE

**Figure 9. CS/PF CROSS SECTION PROFILE
DATA POINT TEMPLATE**

Mock-up List

Central Solenoid Simulated Conductor

Formed radius using 7.5" Radius die, M/U CS-8, -9, -10

Method

The CS mock-up bench bending weld seam orientation trials will be performed using the bench bending fixture. There will be a total of three trials during which the CS samples will be bent using a 7.5" R die. Before bending the cross section profile will be measure at three points, 1" from each ends and at the middle of the sample. Hardness of the conduit will be also be determined. The methodology for bending will be identical to that used in the bench bending springback tests (150°, 130°, 110°, and 90° included angle bends). Sample 1 will bent with the weld seam on the inside diameter of the radius. This will put the weld in compression. Sample 2 will be bent with the weld seam on the outside diameter of the radius. The weld seam in this case will be in tension. Sample 3 will be bent with the seam up (perpendicular to the centerline of the bend).

Roll Bending Reaction Effects TF Mock-ups- Unconstrained and Constrained Coils

Mock-up List

EITHER:

Toroidal Field Simulated Conductor

Roll Formed 60% Scale Model of Single Turn TF Coil M/U TF-7 Unconstrained Coil,
TF-8 Constrained Coil

OR

Central Solenoid Simulated Conductor

Roll Formed 60% Scale Model of Single Turn TF Coil M/U CS-11 Unconstrained Coil, -
12 Constrained Coil

NOTE: Mock-up conduit type used is dependent on timely delivery of GFM TF Simulated Conductor

Method

The Roll Bending Reaction Effects TF mock-up will study the dimensional effects on a D-shaped coil caused by the annealing process which occurs during the reaction cycle. For both mock-ups, a single turn of conductor will be roll formed to create a 60% scale model of a TF magnet coil. The ends will be welded together. Then, the coils will be dimensionally inspected. As a minimum cross section profile data will be taken at four points (the bend radii) and radius profiles will be recorded. The constrained coil mockup M/U TF-7 (or M/U CS-12) will then be fitted with a support structure to restrain coil movement. Both coils will be sent to a vendor to be

put through a representative thermal cycle. Following return to B&W, the constrained coil will be inspected as before prior to removing the support frame. Then, the support frame will be removed from M/U TF-7 (or M/U CS-12). Both coil mock-ups will be inspected in an unconstrained state and their dimensional attributes compared with prior inspection data.

FIGURE 10. MOCK-UP M/U CS-14

Roll Bending Reaction Effects CS Spiral Ramp Transition Elastic Range Test

Mock-up List

Central Solenoid Simulated Conductor

Roll Formed 3 Turns Spiral Model, M/U CS-13 Set-up Piece, -14 Spiral Elastic Range Mock-up

Method

The Roll Bending Reaction Effects Spiral Ramp mock-up will serve to answer two questions. First, we will study whether the layer to layer transition can be formed for the CS coil within 45° of angle sweep with the conduit still within the elastic range. This determines whether a manual transition bend will be required for the CS. Then, the annealing effects of the reaction cycle on the transition geometry will be examined.

Mock-up M/U CS-13 is a set-up piece which will be used to find the optimal roll position for the roll bender. Once these settings have been obtained, Mock-up M/U CS-14 will be run. As a minimum, cross section profile data will be taken at four points on the conduit prior to roll forming. Three turns of the CS conductor will be formed into a spiral (see Figure 10). The ends of the coil will be welded or banded together. Then, the coils will be dimensionally inspected. As a minimum, cross section profile data will be taken at the previously measured four points and the transition region characterized. The mock-up will then be sent to a vendor to be put through a representative thermal cycle. Following return to B&W, the constrained coil will be inspected as

before prior to removing the bands. Mock-up M/U CS-14 will be inspected in an unconstrained state and its dimensional attributes compared with the previous dimensional data.

Roll Bending Reaction Effects on TF Conduit - Twist

Mock-up List

TF Conductor

Roll Bend a 5' Long Piece of TF Conduit to Form a 41.4" Radius, Mock-up M/U TF-5

Method

A five foot section of TF conduit will be cut and inspected at 3 places to determine its cross section profile. (see Figure 9 for the data recording methodology). These cross sections are to be taken 1" from each end and in the middle of the conduit. The Tauring Roll Bender will be used to form a 41.4" nominal radius in the conduit with the weld seam if present on the ID. The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. The bent conductor will be sent to a vendor to be put through a representative thermal cycle. Following its return to B&W, the unconstrained conductor will be inspected as before, and its dimensional attributes compared with prior inspection data.

Roll Bending Weld Seam Orientation

Mock-up List

CS Simulated Conductor

Roll Bend a 10' Long Piece of CS Conduit to Form a 56" Radius, Mock-up M/U CS-15

Method

A ten foot section of CS conduit will be cut and inspected at 3 places to determine its cross section profile. (see Figure 9 for the data recording methodology). These three cross sections are to be taken 1" from each end and in the middle of the conduit. Flatness and twist are to be measured. The Tauring Roll Bender will be used to form a 56" nominal radius in the conduit with the weld seam on the ID. The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. These dimensional attributes will be compared with prior inspection data. This mock-up serves as a baseline for subsequent roll bending mock-ups.

Roll Bending Keystoning/Bulging and Twist Mock-ups

Mock-up List

CS Simulated Conductor

Roll Bend a 10' Long Piece of CS Conduit to Form a 56" Radius, Mock-up M/U CS-16

TF Simulated Conductor

Roll Bend a 10' Long Piece of TF Conduit to Form a 41.4" Radius, Mock-up M/U TF-6

PF Simulated Conductor

Roll Bend a 10' Long Piece of PF Conduit to Form a 145.5" Radius, Mock-up M/U PF-4

Method

Ten foot sections of CS, TF, and PF conduit will be cut and inspected at 3 places to determine its cross section profile. (see Figure 9 for the data recording methodology). These three cross sections are to be taken 1" from each end and in the middle of the conduit. Flatness and twist are to be measured. The Tauring Roll Bender will be used to form a nominal radii in the conduit (CS - 56"R, TF - 41.4"R, PF-145.5"R) with the weld seam on the ID. The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. These dimensional attributes will be compared with prior inspection data.

Roll Bending Cold Working Test Mock-ups

Mock-up List

CS Simulated Conductor

Roll Bend a 6' Long Piece of CS Conduit to Form a 56" Radius, Mock-up M/U CS-17

PF Simulated Conductor

Roll Bend a 6' Long Piece of PF Conduit to Form a 145.5" Radius, Mock-up M/U PF-10

Method

Six foot sections of CS and PF conduit will be cut and inspected at 3 places to determine its cross section profile. (see Figure 9 for the data recording methodology) and overall length. These three cross sections are to be taken 1" from each end and in the middle of the conduit. Flatness, hardness, and twist are to be measured. The Tauring Roll Bender will be used to form a nominal radii in the conduit (CS - 56"R and PF-145.5"R) with the weld seam on the ID. The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. The conduit is then straightened using the roll bender on a best effort basis. This bend, measure, and straighten cycle is to be repeated twice more. Finally, after the final straightening the dimensions are taken again to assess the impact of cold working on the conduit. These dimensional attributes will be compared with prior inspection data. These mock-ups will then proceed to Bench Bending Cold Working testing (see below).

Bench Bending Cold Working Test Mock-ups

Mock-up List

CS Simulated Conductor

Bench Bend a 6' Long Piece of CS Conduit to Form a 7.5" and a 9" Radius, Mock-up M/U CS-17 (Previously, cold worked in the roll former, see above)

PF Simulated Conductor

Bench Bend a 6' Long Piece of PF Conduit to Form a 7.5" and 9" Radius, Mock-up M/U PF-10

Method

The six foot sections of CS and PF conduit previously roll formed during Roll Forming Cold Work testing above were inspected at 3 places to determine its cross section profile. (see Figure 9 for the data recording methodology) and overall length. These three cross sections were taken 1" from each end and in the middle of the conduit. Flatness and twist were also measured. The bench bender will be used to form a nominal radii of 7.5" and 9" in the conduit with the weld seam **on the ID**. The methodology for bending will be identical to that used in the bench bending springback tests (150°, 130°, 110°, and 90° included angle bends). The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. The conduit is then straightened using the roll bender on a best effort basis. The conduit is bent again, as before and measured again. . The conduit is then straightened using the roll bender on a best effort basis. The conduit is bent again, as before and measured again assess the impact of cold working on the conduit. These dimensional attributes will be compared with prior inspection data. These mock-ups will then proceed to Lead & Transition Bending Reaction Effects testing. (see below).

Lead and Transition Bending Reaction Effects Mock-ups

Mock-up List

CS Simulated Conductor

Bench Bending Sample of Simulated CS Conduit, Mock-ups M/U CS-4, -5, -6, -7, and M/U CS-17 (Previously, cold worked in the roll former, see above)

TF Simulated Conductor

Bench Bending Sample of Simulated TF Conduit, Mock-ups M/U TF-1, -2, -3, -4

PF Simulated Conductor

Bench Bending Sample of Simulated PF Conduit, Mock-up M/U PF-10 (Previously, cold worked in the roll former, see above)

Method

The CS, TF, and PF Mock-ups listed above will be sent out with the other reaction effects mock-ups to a heat treating vendor. There they will be subjected to a representative thermal cycle to simulate the reaction process. The mock-ups are to be unconstrained. Following their return

to NNFD, the mock-ups are inspected to determine the conduit cross section profile, bow or sag, radii changes, twist, and hardness . These dimensional attributes will be compared with prior inspection data.

Roll Bending Process Repeatability Mock-ups

Mock-up List

CS Simulated Conductor

Roll Bend 5 10' Long Piece of CS Conduit to Form a 56" Radius, Mock-up M/U CS-18, -19, -20, -21, -22 -

PF Simulated Conductor

Roll Bend a 6' Long Piece of PF Conduit to Form a 145.5" Radius, Mock-up M/U PF-5, -6, -7, -8, -9

Method

Ten foot sections of CS and PF conduit will be cut and inspected at 3 places to determine the cross section profile. (see Figure 9 for the data recording methodology) and overall length. These three cross sections are to be taken 1" from each end and in the middle of the conduit. Flatness, hardness, and twist are to be measured. The Tauring Roll Bender will be used to form a nominal radii in the conduit (CS - 56"R and PF-145.5"R) with the weld seam on the ID. The conduit will again be inspected to determine the cross section at the three points, amount of twist, the relaxed state final as-bent radius, and any bow or sag. These dimensional attributes will be compared with prior inspection data to determine if statistical inferences can be made to determine the process repeatability of roll forming. Since the production roll bender is required by specification to perform much better than the Tauring unit currently being used, the performance data will represent a worst case scenario.

SDRL-37B Bending Development Data Summary Sheet

PC ID	LGTH	Test 1 Description	Test 2 Description	Test 3 Description
CS Conduit Samples				
M/U CS-1	3 ft.	Bench Bending Springback 6" Radius		
M/U CS-2	3 ft.	Bench Bending Springback 6" Radius		
M/U CS-3	3 ft.	Bench Bending Springback 6" Radius		
M/U CS-4	3 ft.	Bench Bending Springback 7.5" Radius	Lead & Transition Bending Reaction Effects	
M/U CS-5	3 ft.	Bench Bending Springback 7.5" Radius	Lead & Transition Bending Reaction Effects	
M/U CS-6	3 ft.	Bench Bending Springback 9" Radius	Lead & Transition Bending Reaction Effects	
M/U CS-7	3 ft.	Bench Bending Springback 9" Radius	Lead & Transition Bending Reaction Effects	
M/U CS-8	3 ft.	Bench Bending Weld Seam Orientation, 7.5"R		
M/U CS-9	3 ft.	Bench Bending Weld Seam Orientation, 7.5"R		
M/U CS-10	3 ft.	Bench Bending Weld Seam Orientation, 7.5"R		
M/U CS-11	10 ft.	Roll Bending Reaction Effects - Spiral Ramp Transition Elastic Range Setup		
M/U CS-12	60 ft.	Roll Bending Reaction Effects - Spiral Ramp Transition Elastic Range		
M/U CS-13	10 ft.	Roll Bending Weld Seam Orientation Tests		
M/U CS-14	10 ft.	Roll Bending Keystoning/Bulging and Twist (Nominal CS Inside Dia.)		
M/U CS-15	6 ft.	Roll Bending Cold Working Test, 3 Cycles	Bench Bending Cold Working Test 7.5" & 9" Radius	Lead & Transition Bending Reaction Effects
M/U CS-16	10 ft.	Roll Bending Process Repeatability - Sample 1		
M/U CS-17	10 ft.	Roll Bending Process Repeatability - Sample 2		
M/U CS-18	10 ft.	Roll Bending Process Repeatability - Sample 3		
M/U CS-19	10 ft.	Roll Bending Process Repeatability - Sample 4		
M/U CS-20	10 ft.	Roll Bending Process Repeatability - Sample 5		
M/U CS-21	3 ft.	Back Bend Springback Sample		
TF Conduit Samples				
M/U TF-1	3 ft.	Bench Bending Springback 7.5" Radius, Easy Way	Lead & Transition Bending Reaction Effects	
M/U TF-2	3 ft.	Bench Bending Springback 7.5" Radius, Hard Way	Lead & Transition Bending Reaction Effects	
M/U TF-3	3 ft.	Bench Bending Springback 9" Radius, Easy Way	Lead & Transition Bending Reaction Effects	
M/U TF-4	3 ft.	Bench Bending Springback 9" Radius, Hard Way	Lead & Transition Bending Reaction Effects	
M/U TF-5	5 ft.	Roll Bending Reaction Effects - Twist		
M/U TF-6	10 ft.	Roll Bending Keystoning/Bulging and Twist (41.4"R)		
M/U TF-7*	30 ft.	Roll Bending Reaction Effects TF 60% Scale - Unconstrained		
M/U TF-8*	30 ft.	Roll Bending Reaction Effects TF 60% Scale - Constrained		
PF Conduit Samples				
M/U PF-1	3 ft.	Bench Bending Springback 9" Radius		
M/U PF-2	3 ft.	Bench Bending Springback 7.5" Radius		
M/U PF-3	3 ft.	Bench Bending Springback 6" Radius		
M/U PF-4	10 ft.	Roll Bending Keystoning/Bulging and Twist (Nom. PF-6 Inside Dia.)		
M/U PF-5	10 ft.	Roll Bending Process Repeatability - Sample 1		
M/U PF-6	10 ft.	Roll Bending Process Repeatability - Sample 2		
M/U PF-7	10 ft.	Roll Bending Process Repeatability - Sample 3		
M/U PF-8	10 ft.	Roll Bending Process Repeatability - Sample 4		
M/U PF-9	10 ft.	Roll Bending Process Repeatability - Sample 5		
M/U PF-10	6 ft.	Roll Bending Cold Working Test, 3 Cycles	Bench Bending Cold Working Test 7.5" & 9" Radius	Lead & Transition Bending Reaction Effects

TOKAMAK PHYSICS EXPERIMENT (TPX)

TOROIDAL FIELD MAGNET DESIGN, DEVELOPMENT AND MANUFACTURE

Contract B235308

SDRL 45

TF Magnet Acceptance Test Plan

August 18, 1995

13-950802-BW-JMaloney-01

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PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

**Toroidal Field Magnet
Acceptance Test Plan**

for the

TOKAMAK PHYSICS EXPERIMENT (TPX) PROJECT

**TPX-PLAN-ATP
REVISION 0**

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1. INTRODUCTION

1.1 PURPOSE

This document describes the acceptance testing to be performed on the Toroidal Field (TF) superconducting coil assemblies for the Tokamak Physics Experiment (TPX) under WBS No. 13. Initial room temperature acceptance tests are performed at the subcontractors site on the production TF coils and assemblies (octant) at critical manufacturing and inspection points with a TPX project option to witness the performance of the testing. Upon delivery to the TPX site or other testing facility, final acceptance testing will be performed by TPX project personnel. Data from the coil verification tests (SDRL 33) will be submitted by the manufacturer as certification of individual coil acceptance (SDRL 44). The Acceptance Test Plan (ATP) contains a subset of the room temperature testing performed under the Verification Test Plan (SDRL 33) that will be performed by TPX project personnel at TBD site to determine whether a magnet assembly can be accepted for installation in the Tokamak reactor. The ATP also contains preliminary recommendations for cold testing to be performed on the TF coil and structure assemblies at the octant level and again after final assembly into the Tokamak reactor. The word 'test' in this document refers to all demonstrations, inspections, and tests as defined in TF Magnet System Requirements document.

1.2 HIERARCHY

The ATP is one of four test plans supporting the TF magnet portion of the TPX project. The other related test plans include: Material and Component, Prototype, and Coil Verification Test Plans. The combination of all test plans comprise a fully integrated testing approach to the TF coil system. Each of the test plans covers a unique series of tests and is designed to provide information throughout the design, manufacturing, and assembly process. The ATP is derived from requirements in the TF Magnet System Requirements Document (TFMSRD(TPX-SPEC-013-0001)). Additional requirements are derived from other documents such as the Failure Modes Effects and Criticality Analysis (FMECA- SDRL 23) and Quality Assurance Plan (SDRL-13). A pictorial of the requirements flow is contained in Appendix A. This pictorial shows the relationship between the related test plans, the various documents that feed or reference the ATP, and the test procedures derived from this plan.

The individual test procedures will describe in detail the step by step process of each specified test. They will include training requirements, equipment, methods, and pass / fail criteria. A Component Fabrication Routing (CFR) will control the activities performed throughout the manufacturing and assembly process at the magnet manufacturers site. The CFR will contain directions to perform the testing and a reference to the test procedure that is to be used. The integration of the manufacturing sequence with the inspections and tests performed is graphically represented in Appendix B. This flow diagram, referred to as Manufacturing, Inspection, and Test Flow Diagram (MITFD), is contained in this document as well as the Coil Verification Test Plan and Quality Assurance Plan.

1.3 SCHEDULE

The ATP will be submitted with the TF Preliminary Design Review (PDR) data package. It will be presented at the PDR for initial approval and again at the TF Final Design Review (FDR) for final approval.

Throughout the preliminary and final design phases, the ATP will evolve with the TF coil requirements. As criteria are established, the test methods and equipment requirements will be finalized, leading to the approval of the individual test procedures.

1.4 TF VERIFICATION FLOW

Prior to execution of the ATP, the material and component testing, prototype testing and coil verification testing will have been completed. The ATP covers the assembly and final testing of the TF magnet assemblies and system.

Room temperature acceptance tests are scheduled at critical points in the coil assembly process and again upon delivery to the TBD site. Cold tests are recommended for both the octant level assemblies and the installed TPX system. The chart in Appendix B shows the integration of the manufacturing and acceptance inspection steps. The tests are scheduled to provide verification and acceptance at the earliest point in the assembly of the coil or where further manufacturing or assembly processes would impede the ability to perform testing.

2. GENERAL TEST OBJECTIVES

The purpose of the ATP is to define a set of tests which are designed to verify, to the extent possible, the acceptability of the TF magnet system after assembly into the coil cases, and upon delivery to the TPX site. The acceptance tests are grouped into three categories: 1) room temperature testing, 2) octant level cold testing, and 3) Tokamak system level testing. The tests contained in this plan are designed to determine the magnets compliance with the TF Magnet System Requirements Document.

The room temperature testing contained in this test plan shall be performed by the magnet manufacturer at the manufacturing site, and again by TPX personnel upon receipt of the octant assemblies. The octant /system level cold tests described in sections 5/6 respectively, will be conducted by TPX personnel. The tests performed on individual TF coils are discussed in detail in the Coil Verification Test Plan (SDRL 33) and will be used by the manufacturer as part of the acceptance data. The scope of this document is to describe the additional tests performed by the magnet manufacturer on TF magnet assemblies in order to verify their acceptability. Upon review and approval of the manufacturer's data, the TPX project will perform the tests contained within the ATP to confirm magnet assembly acceptance. The tests contained within this document are those tests recommended by the manufacturer for the TPX project to perform at the TPX site or other test facility.

Data acquired during manufacturing and assembly will be reported in accordance with internal quality assurance procedures and will be contained within the certification data packet. The data packet is maintained throughout the manufacturing and assembly process and contains all manufacturing, inspection, and test data. The data packet is submitted to the customer as part of the end item certification package (SDRL 44). Test failure disposition and reporting will be in accordance with B&W procedure QT9502 titled "Non Conformance Reporting." Pass/fail criteria for each of the individual tests will be established in conjunction with the TPX project and will be derived from design calculations and possible correlations established during prototype testing.

Test operations by TPX project personnel during acceptance testing are the responsibility of the TPX project, supported by the manufacturer. A copy of data acquired during the final acceptance testing will be forwarded to the manufacturer for completion of test records.

3. TEST IMPLEMENTATION

The following three sections identify the set of tests that are to be performed on the TF magnet assemblies by magnet manufacturer and TPX project personnel to verify acceptability at either the manufacturer's site, TPX site, or other designated testing facility. In addition, the ATP will identify the requirements, methods, and equipment necessary to perform the acceptance tests. These tests have been defined and selected by the Quality Assurance and Test section with input from the Design Engineering, Systems Engineering, and Manufacturing Engineering sections.

The tests are categorized into three distinct groups: room temperature tests, octant level cold tests, and Tokamak system level tests. Octant level cold testing allows for design verification and more importantly manufacturing process verification of the production TF magnets prior to complete assembly in the Tokamak reactor. Without octant level cold testing, any problem with the magnets would require disassembly of the system and therefore risks significant cost and schedule impact to the entire program. Many of the magnet system requirements cannot be tested prior to full system testing, however; there are several critical tests that should be performed prior to system assembly. These critical tests are identified in section 5. Note, the TF magnets will be delivered either as octant assemblies or quadrant assemblies (if feasible) as determined by B&W and the TPX program.

Attached as Appendix E, is an acceptance test matrix that contains detailed information concerning: the tests to be performed, requirements and the specifications that they were derived from, the equipment and sensitivities required to conduct the test, and the data derived from the tests. The test matrix has been designed as a reference tool to identify and detail requirements concerning the implementation of the ATP. The matrix assists in the planning of the individual tests by establishing the testing inputs i.e.: specific tests to be performed, identification and location of derived requirements and rationale (columns one through four). Based upon the input requirements, the test planning is completed by determining the required outputs needed to perform each test i.e.: the required data, phase of production when tests are performed, location of where tests are performed, equipment required to perform tests, and instrument sensitivity. Appendix C contains a table of reference documents supplied by the TPX project, and other organizations that pertain to the individual tests described within this document.

4. ROOM TEMPERATURE TESTS

4.1 DIMENSIONAL INSPECTION

4.1.1 General

In a complete TF octant assembly, the geometric location of the two coils within the structure will be located by permanent references mounted on the TF case exterior. Note, that the choice of these references, whether they are mounts for survey targets or actual case features, will be agreed upon between the manufacturer and the TPX project since these references become datums to properly place the octants during machine assembly.

4.1.2 Method and Acceptance Criteria

Prior to shipment to Lynchburg, the TF case geometry will be visually and dimensionally inspected on the machining center that produces the TF case. In addition, orientation and location of coil-to-case interface standoffs will be inspected. All machining and inspection will be performed with respect to the permanent references on the TF case exterior. Upon receipt at the Lynchburg facility, the coils will be positioned within the case based upon the following two measurements which are made at several (TBD) stations around the coil:

- a) Measurements of cross-section overall height and width will be measured with either a laser tracking system or micrometers;
- b) Distance from VPI surface to outermost conduit turns (currently investigating eddy current techniques).

These two measurements, when combined with a measurement of the distance between the coil VPI surface and the standoffs provides a direct relationship between the coil and the permanent references on the case exterior. The laser tracking measurement system permits direct measurement of the placement of the coil in the case with relation to the fiducials on the case exterior (additional information on this process contained in ŠDRL 32, Coil Assembly Documentation). Following final machining, acceptance dimensional inspection of the finished octant assembly will be performed. This inspection will include verifying the proper location of all interfaces such as:

- a) Nose region
- b) Bolting flanges
- c) Central Solenoid and PF mounting surfaces
- d) Free path for vacuum vessel
- e) Miscellaneous Bus interfaces

4.2 COIL ELECTRICAL CHARACTERISTICS

4.2.1 General

Room temperature electrical measurements will be performed on the TF magnets to verify the coils proper electrical characteristics. These tests provide a quick, simple, low cost, low risk method for determining gross faults within the coil assemblies.

4.2.2 Method and Acceptance Criteria

Standard, low current, four wire methods will be used to determine the dc electrical resistance of the coil. Pass/Fail criteria will initially be established based upon design calculations of the conducting cross sectional area/ unit length and later verified through material and component tests (see also Material & Components Test Plan). This verification will be performed since it is difficult to estimate, a priori, with significant precision the electrical resistance/cross section area of the as-reacted conductor. An inductance and resistance meter which employs a bridge type measurement technique will be used to determine the inductance and quality factor of the coil. Because a coil's inductance is sensitive to both geometry (through self and mutual coupling) and close proximity permeable material, it will change throughout the assembly process. Pass / Fail criteria will be established for each phase of assembly based upon initial design calculations, values measured on insulated mock-up windings using dummy conductor (dummy conductor is defined as In-908 conduit with all copper strand) and values measured during full scale prototype winding.

4.3 INSTRUMENTATION

4.3.1 General

All TF coil instrumentation will be tested upon installation and again upon delivery to the TPX site to assure proper communication and operation, and to verify electrical isolation from high voltage components. TF magnet assemblies or sub-assembly kits will contain the following instrumentation prior to shipment to the customer: 1) voltage taps (direct and co-wound), 2) strain gages, 3) quench detection fiber optics, 4) flow sensors, 5) temperature sensors, and any other instruments installed in or on the coil or case. The type, number, location and sensitivity requirements of the instruments will be determined in conjunction with the TPX project and are addressed in SDRL 31.

Environmental operating conditions, i.e. temperature, magnetic field, high voltage insulation, vacuum, etc., of each measurement sensor will be accounted for in sensor design and evaluation.

4.3.2 Method and Acceptance Criteria

The methods used to test the instrumentation will ensure the proper operation of the instrumentation under room temperature conditions. The instrumentation must meet predetermined acceptance criteria to pass the test. Failure to meet the specified acceptance criteria will result in instrumentation replacement or repair where possible. Criteria for failure response will be detailed in the individual test procedures.

As a preliminary list, the instrumentation acceptance tests will include:

Measurement	Type	Type of Test
Voltage Taps	Co-wound Coax. Inductive - TBD	continuity, dc resistance, inductance (inductive type only), insulation integrity, time domain reflectometry (TDR see ref. No: 14)
Strain Gages	TBD	continuity, dc resistance, insulation integrity, calibration
QD fiber optics	TBD	optical time domain reflectometry (OTDR)
He flow sensors	TBD	continuity, insulation integrity, calibration
Temp. sensors	Cernox	continuity, insulation integrity, calibration

4.4 COIL INSULATION INTEGRITY

4.4.1 General

The insulation of the TF coil turn to turn, layer to layer, and coil to ground are to be tested after the magnet assembly is delivered to the TPX site. The insulation must withstand the steady state operational voltages as well as the higher level transient voltages created due to rapid (and repeated) current discharge during a quench. The maximum voltage generated due to quench is estimated at 15 kV across the TF bus leads (ref.: TPX-STND-001) and ± 7.5 kV dc with respect to ground. Issues pertaining to the duration of test at peak voltage, maximum charge/discharge time, No. of cycles, etc. are TBD and will be determined in conjunction with the TPX project based upon the insulation studies described in the Materials and Components Test Plan (SDRL 34) of Phase II, insulated mock-ups using dummy conductor, and full scale prototype testing.

B&W is initially recommending that high voltage dc Hipot testing to a level of 16 kV ($2 \times V_{\text{peak}} + 1\text{kV}$) only be performed on the insulated mock-up winding and the full scale prototype winding. For the remaining production TF magnets, coil to ground insulation integrity will be verified through: a) process control during manufacturing, b) dc Hipot testing to 7.5 kV (TPX-ICDP-1342-0010), and c) insulation resistance testing < 1 kV (sometimes referred to as megger testing). The last test will provide the insulation resistance value which will verify that at an applied voltage of 16 kV, the leakage current should be less than 0.1 mA. The rationale for not performing dc Hipot testing to 16 kV on the production TF coils, is because of the relatively large amount of capacitance within the winding pack. Thus, a TF coil can store a significant amount of charge during these tests. Any failure during this test could result in catastrophic and irreparable damage to the coil. This could result in a significant cost and schedule impact.

4.4.2 Method and Acceptance Criteria

In order to avoid permanent or irreparable damage, low voltage resistance and inductance measurements will be performed to verify that there are no gross faults prior to the use of high voltage measurement techniques. Turn to turn and layer to layer insulation measurements will use impulse measurements with a test levels of ~ 2900 V (i.e. $2 \times V_{\text{peak}}/16 + 1\text{kV}$).

Based upon the rationale stated in section 4.4.1, coil to ground measurements will be made with a dc high potential meter to an applied level 16 kV ($2 \times$ quench voltage $+ 1\text{kV}$) after the second VPI cycle on insulated mock-ups and the prototype coils and 7.5 kV on production TF coils. The selection of this test voltage will be supported through testing performed under the Material and Component Test Plan. All Hipot testing on production TF coils will be limited to < 20 s at peak voltage (~ 4 -5 quench discharge time constants). In addition, qualification tests will be performed using rented equipment (see Material and Components Test Plan) to determine the need and cost/benefit ratio for Tan δ tests on insulation loss characteristics.

Ground wrap to case insulation testing involves the application of a temporary conductive wrap after the second VPI cycle. The ground wrap to case test will use an applied voltage of 1 kV. To pass the tests, the insulation must withstand the test voltages without signs of visual flaws, TBD loss, or 1 mA leakage current. The tests will be conducted in air at room temperature and pressure.

4.5 STRUCTURE INSULATION INTEGRITY

4.5.1 General

Once the TF coil is installed in the TF structure, there must be voltage isolation, between the coil and the grounded structure exceeding the maximum quench voltage. Many components such as the helium isolators, coil case, etc. must withstand the related voltages. Each octant of the TF magnet assembly shall be electrically isolated from all other assemblies and grounded with a single point ground. The leakage current between assemblies in air shall not be more than 1 mA at a standoff voltage of 1 kV with the single point ground lifted. Coil to ground insulation must exceed 16 kV for prototype and insulated mock-ups and 7.5 kV for production magnets, while other components must withstand 1 kV voltages.

4.5.2 Method and Acceptance Criteria

In order to minimize the potential for permanent or irreparable damage, a simple low voltage continuity check will be used to verify that the insulation resistance level exceeds 1 M Ω for 1 kV tests and 160 M Ω for both 16 and 7.5 kV tests (see section 4.4.1), prior to using any high voltage equipment. A dc high potential meter will be used to determine coil to ground insulation integrity. The production assembly must withstand the 7.5 kV applied voltage on the coil with no more than 0.1 mA leakage current through isolators and insulation to pass the test. The magnet assembly shall be disconnected from the single point ground and tested at 1 kV against surrounding assemblies / components. The leakage current must be below 1 mA.

4.6 FLOW IMPEDANCE

4.6.1 General

The CICC of the TF magnet is the cooling channel and must sustain a predetermined coolant flow rate in order to maintain operational temperatures. Various operations, such as the attachment of helium stub tubes, splice joint fabrication, etc. have the ability to constrict or disrupt the flow in the CICC.

4.6.2 Method and Acceptance Criteria

Flow through conduit can be accurately correlated between largely different flowing conditions given equivalent Reynolds numbers. For the TF CICC at room temperature flowing conditions, pressures in excess of 6 MPa would be required to achieve an equivalent Reynolds number to that of the actual steady state flowing conditions. An alternative approach is to base the warm test flow on standard flow equations using empirical correlation of friction factors derived for CICC. The friction factor correlation used by E. Tada (see ref. 13, Appendix C) gives good results for Reynolds numbers between 10^2 and 10^4 ; a range which is compatible with the actual flow conditions. The test fluid must have a sufficiently high density to viscosity ratio in order to attain the minimum Reynolds numbers given above. Excluding LN₂ cooled fluids due to cost considerations, the most appropriate choice of a testing fluid at room temperature conditions is gaseous argon. In this test, gaseous argon will flow through the entire coil. The coil will be connected and tested in the same manner as during operation, with multiple inlet and outlet ports. Tests will also be performed to determine flow matching between coolant paths. This test method and the acceptance criteria will be investigated and established under the Material and Component Test Plan during trials on dummy and prototype conduit and conductor.

4.7 HELIUM LEAK TESTING

4.7.1 General

Leak testing of accessible components will be used to verify welds and closures to ensure that they can maintain the vacuum levels specified without any leaks over the stated amounts. Areas that will be tested are: vacuum welds, piping assemblies, coil to coil connections, and TF case cooling channels.

4.7.2 Method and Acceptance Criteria

Standard vacuum helium leak testing equipment and methods will be employed on component / subassembly level. Pass / Fail criteria pertaining to the helium leak detector sensitivity and maximum allowable leak rate, at specified ambient conditions, will be determined on a component / assembly basis but will fall near the range of 10^{-7} to 10^{-9} Pa - m³/s. Components or assemblies that are difficult to access or evacuate will use a pressure testing arrangement that employs one of two potential methods: a) an acoustic pickup that detects the sonic emissions of pressurized gas leaking through an orifice or b) a hand held wand which draws in air from around the un-insulated coil pack and analyzes it for helium content. Investigation of these detection methods will be explored under the Material and Components testing (SDRL 34) plan for their sensitivity and feasibility with CICC leak detection.

4.8 WELD INSPECTION -

4.8.1 General

Various welds on the TF case and piping require tight process control, monitoring, and inspection. The case closures and chimney welds must be performed so as not to warp the TF case or damage the installed coil.

4.8.2 Method and Acceptance Criteria

In addition to the process monitoring described in §4.10, welds on the case will undergo standard die penetration tests to verify that there are no surface cracks that would effect the performance of the connection. The case closure weld will also be subjected to ultra-sonic (UT) inspection to verify that the weld attained full penetration and that the interior of the weld is structurally sound. These tests will be performed after the weld has been completed and before any further magnet processing has occurred. A crack or imperfection detected by these inspection techniques will require a review of the data and formulation of corrective action through a material review board and non-conformance reporting procedures.

4.9 VISUAL INSPECTIONS

Visual inspections shall be performed throughout the manufacturing process to verify that the magnet assembly appears to be clean and undamaged. The magnet assembly will be inspected at several designated stages during fabrication for signs of damage, foreign particles, and other contaminants.

4.10 PROCESS VERIFICATION

Processes parameters for complex operations such as welding, bolting, coil potting, instrumentation installation, lead bending and forming, splice fabrication, etc. will be checked prior to starting the process, monitored during the operation, and again verified after the operation is complete. The parameters will be detailed in a component fabrication routing (CFR) document that lists every manufacturing and inspection step performed. This document contains the parameters, procedures, and sign-offs for all process criteria and inspections. Critical parameters will be monitored continuously throughout the operation and may be recorded through the data monitoring / control system of the process equipment.

5. OCTANT LEVEL COLD TESTING

The TF Magnet Failure Modes Effects and Criticality Analysis (SDRL 23) has identified a number of potential defects that could prevent the magnet from reaching its required current and magnetic field, but cannot be detected until the magnet is cold tested.

These processing defects include:

- A defect in the superconductor as received for coil fabrication (processing anomalies occurring during strand fabrication, cabling, or conduit installation).
- Conductor damage during winding, particularly during conduit piercing and helium stub welding.
- Damage during conductor termination, or a defect in the splicing process.
- Conductor overstrain after reaction, during insulation or later process steps.

Failure of the TF magnet to reach its required 4 T (@ $r=2.25$ m) operating field could compromise the objectives of the TPX project. The earliest cold test planned at present occurs after assembly of the complete cold mass and cryostat in the TPX test cell, approximately one year after TF magnet delivery. From the PPPL integration plan, we estimate that the time required to disassemble the cryostat and cold mass, replace a defective coil, and rebuild the system to return to the same point on the integration schedule, would be more than one year -- assuming that a spare coil were available. During this period of delay, work on later stages of Tokamak integration would essentially be stopped.

If the TPX project schedule is stretched due to funding limitations, then an earlier cold test of individual octants may be possible, mitigating the risk of a major project delay during integration at minimal added cost. Octant-level tests could use the same facility established for TF prototype testing. The test objective would be limited to verification of the coils' ability to achieve the required operating current. At the operating current and temperature, the magnetic field and stress in the octant configuration will be less than that in the system level operation. It is possible, however, to determine superconducting margin characteristics by increasing either the temperature, current, magnetic field, strain or a combination of these. The safest and most straightforward method to accomplish this is to raise the helium temperature of the inlet flow, at operating current, to a similar test point on the Nb_3Sn critical surface. Specific test conditions will be determined in the course of prototype test planning in Phase II.

Further risk mitigation would be achieved if a complete TF octant were built as a spare. The process of removing the prototype coil from its case after potting and testing has not been defined, and will be high in risk. Even if the prototype coil is successfully separated from its case after testing and before the initial Tokamak cold test, the time to recover from a magnet failure, if it occurs, will be greater than if a complete octant were available.

The concept of building spare coils is consistent with the TFTR project, for which two extra TF coils were fabricated.

5.1 COOL DOWN

The magnet assembly shall be capable of cool down to operating temperature in accordance with (IAW) TFMSRD §3.2.1.6.a.

5.2 FLOW RATES THROUGH CICC

Cooldown, warm-up, steady state, and quench recovery flow rates shall be IAW TFMSRD §3.1.2.9 as measured with the inlet / outlet He flow meters.

5.3 PRESSURES IN CICC

Operational and quench helium pressures shall fall within the pressure profiles prescribed in TBD. The pressure will be measured at the inlet/outlet quench detection pressure gauges.

5.4 4K INSULATION INTEGRITY

Tests shall be performed to ensure that the turn to turn, layer to layer, and coil to ground insulation's meets the criteria prescribed in TFMSRD §3.2.1.4. Tests shall include dc high potential and impulse tests.

5.5 QUENCH DETECTION INSTRUMENTATION

The instrumentation installed on the magnet shall be tested to ensure proper operation and sufficient sensitivity to detect a quench IAW TFMSRD §3.2.1.3.d. Tests will be performed on the: flow meters for enhanced flow and reverse flow conditions, co-wound and direct wired voltage taps for voltage sensitivity, and the co-wound fiber optic cable for temperature sensitivity.

5.6 OPERATING CURRENT

The magnet assembly shall be tested to ensure that it is capable of reaching and maintaining operational currents IAW TFMSRD §3.2.1.3.b. The current flow shall be tested in both directions to verify bi-directional operation IAW TFMSRD §3.2.1.1.b.

5.7 OPERATIONAL RAMP RATES

The magnet assembly shall be tested to ensure that the coil's ramp rate dependency does not limit the prescribed operation IAW TFMSRD §3.2.1.3.b.

5.8 REVERSE ACTION W/O QUENCH

The magnet shall be able to reverse action, i.e. ramp up and back down, without triggering a quench IAW TFMSRD §3.2.1.3.b.

5.9 FIELD STRENGTH AT MAJOR RADIUS

The magnetic field shall be measured with a Hall probe at TBD location and shall meet TBD requirement. The magnetic field shall not be mapped during this test.

5.10 SPLICE RESISTANCE

The voltage drop across the splice shall be measured with the splice voltage taps and shall not exceed TBD volts at operating current IAW TFMSRD § TBD.

5.11 HE FLOW THROUGH SPLICE

The He cooling flow through the splice cooling channels shall be IAW TFMSRD § TBD.

5.12 HELIUM VOLTAGE ISOLATOR PERFORMANCE

The voltage isolation of the helium voltage isolators shall be tested with a dc high potential meter. The isolation level shall exceed 16 kV with a leakage current of < 0.1 mA IAW TFMSRD §3.2.1.4.

5.13 WARM UP

The magnet assembly shall be capable of warming from operating temperature to room temperature within the times prescribed in TFMSRD §3.2.1.6.b.

6. SYSTEM LEVEL TESTING

Once the Tokamak reactor is assembled, a number of tests must be performed to ensure proper operation and integration of the many sub-systems that comprise the reactor. Many of the specification requirements for the TF magnets can not be tested prior to complete assembly in the Tokamak due to influences of other magnets, assembled geometry, handling damage, etc. For example, it is not until the TF magnets are completely assembled as a full ring that the magnetic field can be mapped with any meaningful results. This section recommends tests to be performed and data to be gathered to verify that the TF magnets comply with the specifications. The tests will be performed by TPX personnel at the TPX site upon completion of the Tokamak assembly. The TF magnet tests should be performed as part of the TPX system commissioning. The manufacturer recommends that the following tests be performed to ensure specification compliance.

6.1 SINGLE POINT GROUNDING

The single point grounding system shall be tested by removing the grounding point and testing instrumentation and component isolation from ground. The tests shall be performed with a dc high potential meter with an applied voltage of 1 kV and leakage current of < 1 mA IAW TFMSRD §3.2.1.5.

6.2 INSTRUMENTATION CALIBRATION

All installed instrumentation shall be calibrated IAW the instrument calibration specifications or special calibration procedures. The instrumentation calibration shall cover the expected operating range of the instruments and the operating environment of the instruments.

6.3 COOL DOWN

The magnet assembly shall be capable of cool down to operating temperature within 10 days in accordance with (IAW) TFMSRD §3.2.1.6.

6.4 CASE STRESSES

Case stress shall not exceed the criteria for combined operating loads IAW TFMSRD §3.2.5.2.a. Stresses shall be measured with strain gauges placed at critical points throughout the structure.

6.5 FLOW RATES THROUGH CICC

Cooldown, warm-up, steady state, and quench recovery flow rates shall be IAW TFMSRD §3.1.2.9 as measured with the inlet / outlet He flow meters.

6.6 PRESSURES IN CICC

Operational and quench He pressures shall fall within the pressure profiles prescribed in TBD. The pressure will be measured at the inlet/outlet pressure gauges.

6.7 4K INSULATION INTEGRITY

Tests shall be performed to ensure that the turn to turn, layer to layer, and coil to ground insulation's meets the criteria prescribed in TFMSRD §3.2.1.4. Tests shall include dc high potential and impulse tests.

6.8 QUENCH DETECTION INSTRUMENTATION

The instrumentation installed on the magnet shall be tested to ensure proper operation and sufficient sensitivity to detect a quench IAW TFMSRD §3.2.1.3.d. Tests will be performed on the: flow meters for enhanced flow and reverse flow conditions, pressure transducers for pressure surges, co-wound and direct wired voltage taps for voltage sensitivity, and the co-wound fiber optic cable for temperature sensitivity.

6.9 OPERATING CURRENT

The magnet assembly shall be tested to ensure that it is capable of reaching and maintaining operational currents IAW TFMSRD §3.2.1.3.b. The current flow shall be tested in both directions to verify bi-directional operation IAW TFMSRD §3.2.1.1.b.

6.10 OPERATIONAL RAMP RATES

The magnet assembly shall be tested to ensure that the coil's ramp rate dependency does not limit the prescribed operation IAW TFMSRD §3.2.1.3.b.

6.11 REVERSE ACTION W/O QUENCH

The magnet shall be able to reverse action, i.e. ramp up and back down, without triggering a quench IAW TFMSRD §3.2.1.3.b.

6.12 MAGNETIC FIELD

The magnetic field produced by the TF magnets is used to confine the plasma during operation and is crucial to the successful operation of the system. Magnetic field errors can result in plasma instabilities and (or) plasma disruption. The only time that the fields can be measured with meaningful results is after the completion of the TPX installation. The types of field errors which need to be measured and controlled to acceptable levels are: a) field ripple ($\Delta B/|B_0|$) and b) magnetic field harmonics ($|\delta B_{r,m,n}/B_0|$). The allowed values for the magnetic field errors are listed in TFMSRD §3.2.1.2.

6.13 SPLICE RESISTANCE

The voltage drop across the splice shall be measured with the splice voltage taps and shall not exceed TBD volts at operating current IAW TBD.

6.14 HE FLOW THROUGH SPLICE

The He cooling flow through the splice cooling channels shall be IAW TBD.

6.15 HELIUM VOLTAGE ISOLATOR PERFORMANCE

The voltage isolation of the Helium voltage isolators shall be tested with a dc high potential meter. The isolation level shall exceed 16 kV with a leakage current of < 1 mA IAW TFMSRD §3.2.1.4.

6.16 WARM UP

The magnet assembly shall be capable of warming from operating temperature to room temperature within the times prescribed in TFMSRD §3.2.1.6.b.

7. CONCLUSION / FUTURE WORK

The ATP is one of four integral test plans which are designed to verify the performance of the TF magnet. The ATP in conjunction with the Coil Verification Test Plan are the highest levels of acceptance test planning. Future work to formalize the completion and integration of the ATP in the TF coil program will include the following: 1) establishment of pass/fail criteria for tests outlined in acceptance test matrix, 2) periodic update of the ATP to reflect modifications in design derived requirements, 3) development of cold test plan, 4) integration with supplemental test plans, i.e. FMECA and Quality Assurance Plan, for a comprehensive TF testing approach, 5) completion of detailed test procedures, 6) determine facility and equipment requirements for testing, 7) develop test technician training requirements.

Appendix A

Information Flow Diagram

Appendix B

Appendix C

Reference List

1. GRD, GENERAL REQUIREMENTS DOCUMENT
2. TPX-STND-001, TPX STRUCTURAL AND CRYOGENIC DESIGN CRITERIA
3. 13-930319 -LLNL/WHASSENZAHN-01, SYSTEM DESIGN DESCRIPTION TF MAGNETS
4. SYSTEM DESIGN DESCRIPTION, TPX POWER SYSTEMS
5. SOW, TPX TECHNICAL SCOPE OF WORK, TPX MAGNET SYSTEM
6. SDRL - 13, QA PLAN
7. SDRL - 20, TF MAGNET COIL SPECIFICATION
8. SDRL - 23, FMECA
9. SDRL - 32, COIL ASSEMBLY DOCUMENTATION
10. SDRL - 34, MATERIAL AND COMPONENT TEST PLAN
11. SDRL - 35, PROTOTYPE TEST PLAN
12. SDRL - 45, ACCEPTANCE TEST PLAN
13. E. TADA, ET AL, "STEADY PRESSURE DROP AND QUENCH PRESSURE RISE IN CABLE-IN - CONDUIT SUPERCONDUCTORS"; CRYOGENICS 32:829 (1992)
14. C.M. REY AND K.C. HENDERSON, "AN EXPERIMENTAL INVESTIGATION OF THE APPLICATION OF TIME DOMAIN REFLECTOMETRY TO SSC MAGNET STRAND INSPECTION," B&W REF. NO. RDD:93:62072-001-001:01 JUNE 1992.

Appendix D

TF Magnet System Quality Conformance Matrix (Ref. TPX-SPEC-013-0001)

ATP Par.	TFMSRD Par.		Analysis	Demo	Inspection	Test	N/A
	3.1	Item Definition					x
	3.1.1	Prime Item Diagrams			x		
	3.1.2	Interface Definition					x
6	3.1.2.1	Vacuum Vessel Interface (WBS 12)		x	x	S	
6	3.1.2.2	PF Magnet System Interfaces (WBS 14)		x	x	S	
6	3.1.2.3	Cryostat Interfaces (WBS 15)		x	x	S	
6	3.1.2.4	Tokamak Support Structure Interfaces (WBS 16)		x	x	S	
6	3.1.2.5	Field Error Correction Coil Interfaces (WBS 19)		x	x	S	
6	3.1.2.6	Vacuum Pumping System Interfaces (WBS 34)		x	x	S	
6	3.1.2.7	Electrical Power System Interfaces (WBS 42)		x		S	
6	3.1.2.8	Instrumentation and Control Interfaces (WBS 61)		x		S	
6	3.1.2.9	Cryogenic Equipment Interfaces (WBS 72)		x		S	
	3.1.2.10	Tokamak Assembly Interfaces (WBS 95)		x			
	3.1.3	Critical Component List					x
QA Plan	3.1.3.1	TF Conductor (WBS 132)			x		
	3.1.3.2	TF Magnet (WBS 133)		x			
	3.1.3.3	TF Local Instrum. and Control (WBS 135)		x			
	3.1.3.4	TF Bus and Leads (WBS 136)		x			
	3.1.3.5	TPX Coil Winding Equipment		x			
	3.1.3.6	TPX Coil Reaction Equipment		x			
	3.1.3.7	TPX Coil VPI Equipment		x			
	3.2	Characteristics					x
	3.2.1	Performance					x
6	3.2.1.1	Operating States	x			S	
6	3.2.1.2	Magnetic Field	x			S	
5, 6	3.2.1.3	Quench Stability	x			P, S	
4.4, 4.5, 5, 6	3.2.1.4	High Voltage Breakdown	x			A, P, S	
4.5	3.2.1.5	Electrical Isolation and Grounding		x		A, P, S	
4.3, 5, 6	3.2.1.6	Instrumentation and Quench Detection		x		A, P, S	
6	3.2.1.7	Cool-down and Warm-up	x			S	
	3.2.1.8	Operating Cycles and Useful Life	x				
	3.2.2	Physical Characteristics					x
	3.2.2.1	Size and Weight		x			

ATP Par.	TFMSRD Par.		Analysis	Demo	Inspection	Test	N/A
	3.2.3	Reliability and Availability	x				
	3.2.4	Maintainability		x			
	3.2.5	Environmental Conditions					x
	3.2.5.1	Shipping and Storage Environments	x	x			
	3.2.5.2	Operating Environments	x		--		
	3.2.6	Transportability		x			
	3.3	Design and Construction					x
	3.3.1	Materials, Processes, and Parts					x
	3.3.1.1	Material Selection		x			
4.7, 4.8	3.3.1.2	Weldments	x		x		
	3.3.2	Reserved					x
QA Plan	3.3.3	Nameplates and Product Marking			x		
QA Plan	3.3.4	Workmanship			x		
	3.3.5	Interchangeability of Components		x			
	3.3.6	Safety		x			
	3.3.7	Human Factors		x			
	3.3.8	Structural Integrity					x
	3.3.8.1	TF Magnet Structures	x				
	3.3.8.2	Support Equipment	x				
	3.4	Documentation					x
	3.4.1	Specifications			x		
	3.4.2	Design Drawings			x		
	3.4.3	Plans			x		
	3.5	Logistics					x
	3.5.1	Maintenance		x			
	3.5.2	Supply		x			
	3.5.3	Facilities and Facility Equipment		x			
	3.6	Personnel and Training					x
	3.6.1	Personnel		x			
	3.6.2	Training		x			
	3.7	Major Component Characteristics					x
Coil Verification Test Plan 6 4.3, 5, 6 5, 6	3.7.1	TF Magnet Coil	x			A, P, S	
	3.7.2	TF Magnet Structure	x			S	
	3.7.3	TF Local Instrumentation and Control		x	--	A, S	
	3.7.4	TF Bus and Leads	x	x		S	

Testing code: A - Factory Acceptance Test; P - Prototype Test; S - Tokamak Systems Test

Appendix Test Requirements

Verification Test	Derived From	Test Loc.	Rational for performing test	Phase of Production	
1. Coil Insulation Integrity	TFMCS §3.2.1.1 §3.2.2.3	B&W	<ul style="list-style-type: none"> • Turn to Turn Insulation Integrity • Coil to Ground Insulation Integrity 	<ul style="list-style-type: none"> • During Winding • Post-Insulation • Post VPI 	• • • •
2. Coil Electrical Characteristics	TFMCS §3.2.1.1	B&W	<ul style="list-style-type: none"> • Basic electrical properties of coil 	<ul style="list-style-type: none"> • Throughout Manufacturing 	• •
3. Pressure Testing	TFMCS §3.2.1.2	B&W	<ul style="list-style-type: none"> • Verify CICC Pressure Rating 	<ul style="list-style-type: none"> • After Reaction 	•
4. Helium Leak Testing	TFMCS §3.2.1.2	B&W	<ul style="list-style-type: none"> • Weld integrity 	<ul style="list-style-type: none"> • Throughout Manufacturing 	•
5. Flow Impedance	TFMCS §3.2.1.3	B&W	<ul style="list-style-type: none"> • Verify pressure drop through winding does not exceed limit. • Verify pancake variability does not exceed limit 	<ul style="list-style-type: none"> • Pre/Post Winding / Helium stub installation 	• • •
6. Instrumentation	TFMCS §3.2.1.4	B&W	<ul style="list-style-type: none"> • Verify that installed instrumentation is functioning. 	<ul style="list-style-type: none"> • Throughout Manufacturing 	• • •
7. Nb ₃ Sn Conductor Characteristics	TFMCS §3.3.1.5	Outside Lab	<ul style="list-style-type: none"> • Verify Critical Current • Reaction Cycle Verification 	<ul style="list-style-type: none"> • Post-Reacting 	• •
8. Dimensional Inspection	TFMCS §3.2.2.1	B&W	<ul style="list-style-type: none"> • As built / reacted key dimensions 	<ul style="list-style-type: none"> • Throughout Manufacturing 	•
9. Weld Inspection	TFMCS §3.3.1.2	B&W	<ul style="list-style-type: none"> • Ensure high quality welds 	<ul style="list-style-type: none"> • Post Helium Stub Attachment • Post Splice Block Attachment 	•
10. CICC Crack Detection	TFMCS § TBD	B&W	<ul style="list-style-type: none"> • Cracks less than maximum allowable size 	<ul style="list-style-type: none"> • Post-Reacting 	•
11. Conductor Splice	TBD	B&W	<ul style="list-style-type: none"> • Ensure solid bond between splice block and conductor 	<ul style="list-style-type: none"> • Post Splice Block Attachment 	•

ix E

ents Matrix

Specification Requirement & Source / Test Requirement	Equipment Required	Equipment Sensitivity Required
Turn = 10V inductive voltage during fast dump - test 700 volts Impulse / induced (2x coil +1) (per WBS 42- Power Supplies and Quench Protection) Layer to layer = 240V inductive during fast dump to Ground >7.5kV - Quench Voltage - Test to =16kV dc Hipot (per WBS 42- Power Supplies and Quench Protection) Ground wrap to case (with ground point lifted) 1kV dc	<ul style="list-style-type: none"> • dc High Potential Meter • Tan-Delta Meter • Induced Voltage System • Impulse test system • Shell for in process monitoring 	<ul style="list-style-type: none"> • dc Hipot ⇒16kV production test ⇒0.01mA current trip • Impulse ⇒2.7kV • Induced Voltage ⇒2.7kV @ TBD Hz • Tan δ ⇒11.3kV AC ⇒60Hz
Inductance ≈ 50.7 mH for single coil Resistance ≈ 0.173 Ω per coil	<ul style="list-style-type: none"> • Test Cart system (power supply, volt meter, inductance meter) 	<ul style="list-style-type: none"> • Power Supply ⇒10 amp x 2 V • LCR meter ⇒50.7 mH • Volt meter ⇒0.1mV accuracy
CC - 370 psig w/ TBD leakage.	<ul style="list-style-type: none"> • Pressurized Gas source • Pressure Transducers 	<ul style="list-style-type: none"> • TBD
Pressurized conduit w/ TBD leakage	<ul style="list-style-type: none"> • Sonic Leak detection system 	⇒Background Null ⇒1x10 ^{-TBD} l/s
Operation SC He @ 5 ATM inlet - 2-3 ATM outlet g/s in TF coil SC He (7g/s through each winding) Argon Test (11 ATM drop @ 1.71 SCFM per Kelly (on))	<ul style="list-style-type: none"> • Flow meters • Pressure transducers • Pressurized Argon supply 	<ul style="list-style-type: none"> • Flow meter ⇒2 SCFM, .01 res • Pressure Transducer ⇒.05 psi
Fiber signal distance = TBD Wound voltage tap Ohms = TBD Wound voltage tap inductance	<ul style="list-style-type: none"> • Volt Meter • Current Supplies • Inductance meter • Fiber Optic Meter • TDR meter 	<ul style="list-style-type: none"> • TBD
Winding strands reacted with coil.	<ul style="list-style-type: none"> • Outside Lab 	<ul style="list-style-type: none"> • N/A
Drawings	<ul style="list-style-type: none"> • Miscellaneous Dimensional Measurement Equipment 	<ul style="list-style-type: none"> • TBD
D	<ul style="list-style-type: none"> • Die Penetration • Temperature Sticks • Ultra-Sonics 	<ul style="list-style-type: none"> • TBD
Maximum allowable crack size = Long Crack - Depth not to exceed 10% wall thickness Short Crack - under 55 mils long, depth not to exceed 20% of wall thickness	<ul style="list-style-type: none"> • Eddy Current Analysis system 	<ul style="list-style-type: none"> • TBD
D	<ul style="list-style-type: none"> • Ultra Sonics • Test Cart equipment 	<ul style="list-style-type: none"> • TBD

END DATE
6-18-96