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DESIGNING MAGNETIC SYSTEMS FOR RELIABILITY

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Abstract

Designing magnetic systems is an iterative process in which the requirements are set, a design is developed, materials and manufacturing processes are defined, interrelationships with the various elements of the system are established, engineering analyses are performed, and fault modes and effects are studied.

Reliability requires that all elements of the design process, from the seemingly most straightforward such as utilities connection design and implementation, to the most sophisticated such as advanced finite element analyses, receives a balanced and appropriate level of attention. D.B. Montgomery's study of magnet failures[1] has shown that the predominance of magnet failures tend not to be in the most intensively engineered areas, but are associated with insulation, leads, and unanticipated conditions. TFTR, JET, JT-60, and PBX are all major tokamaks which have suffered loss of reliability due to water leaks. Similarly the majority of causes of loss of magnet reliability at PPPL has not been in the sophisticated areas of the design but are due to difficulties associated with coolant connections, bus connections, and external structural connections. Looking towards the future, the major next-devices such as BPX and ITER are more costly and complex than any of their predecessors and are pressing the bounds of operating levels, materials, and fabrication. Emphasis on reliability is a must as the fusion program enters a phase where there are fewer, but very costly devices with the goal of reaching a reactor prototype stage in the next two or three decades. This paper reviews some of the magnet reliability issues which PPPL has faced over the years, the lessions learned from them, and magnet design and fabrication practices which have been found to contribute to magnet reliability.

Impacts on Reliability: PPPL's Experience

Much insight as to the nature of operational difficulties can be learned by reviewing field experience; with this in mind, listed below are the most memorable from the last three decades:

• The bus connection panel for the divertor on the C-Stellerator had non-interchangeable parts to assure proper connection for either the divertor or non-divertor mode operation. Nevertheless, a high-current fault occurred when operation began after a mode change. The bus reconnection parts were found to be properly positioned, but the bolts were inadvertently left loose. This led to the use of check lists with double-checking by independent personnel for critical operations and verification of proper joint make-up by measurement of joint resistance and bolt torque.

• A TF coil to bus electrical connection on the ATC machine was improperly made up in such a way that there was only a single line of contact with much of the current therefore being shunted through the silicon bronze bolts which clamped the joint. With repeated pulsing, the silicon-bronze bolts heated and elongated, increasing the resistance at the line of contact and shunting more current through the bolts. This continued until the bolts melted, allowing the joint to open with resulting arcing and erosion of copper. The repair involved chamfering of the epoxy/glass around the coil contact surface and the copper connector to ensure that copper to copper contact is achieved. As a general design principle, recessed electrical connections should be avoided to preclude this possibility.

• The PLT machine initially used an aluminum coaxial bus system entirely made of high-purity aluminum. Creep allowed the joint contact pressure to relax, ultimately resulting in arcing at the contact surfaces and deep pitting which required replacement. This design, with modifications was used successfully on PBX. The modifications included using stronger aluminum alloys welded to the coax at the connection ends, adding belleville washers, improved surface preparation before and during the application of contact grease, and improved maintenance procedures such as installing and periodic monitoring of thermal stickers, periodic bolt torque checks, and monitoring of joint resistances with a digital low resistance ohm meter.

• A pair of OH coil leads of the PLT machine was clamped together with G-10. The laminate orientation was such that it failed through the plies, permitting the leads to flex until one developed a water leak. Since then, clamps are, whenever possible, made of metal with electrical insulation only acting in compression.

• Common size and type of inlet and outlet water fittings resulted in incorrect reconnection to a PLT TF coil after a maintenance procedure. The resulting loss of flow in several flow paths was not detected by flow instrumentation, which monitored several paths in parallel. This arrangement was such that the partial loss of flow was in the "dead band" of the instrumentation and permitted overheating to occur to the point that insulation between turns was charred. An electrical jumper had to be installed between the affected turns. Since then, we strive to clearly label, or preferably provide different inlet and outlet sizes and minimize ganging of flow paths into a flow meter.

• The PF interconnecting bus on PBX was located as much as possible in the shadow of the TF coils in the annulus between the vacuum vessel and bore of the TF coils so as to maximize access to the tokamak. However, in retrospect a better balance between consideration of access and maintainability and reliability should have been made. This location has made lead bracing and maintenance of the connections very difficult. Although no failures have occurred, it was necessary to revise the bracing and has hampered routine maintenance. Locating bus in the TF bore immerses them in the TF field, which increases bracing demands. Factors such as the length difference of two curved leads which are clamped to each other become important to consider when making provisions for bracing.

• A water leak developed in the OH lead of PBX ~ 4 years ago. Although it has not absolutely been determined where the leak occurred, it is felt that it is probably at a lead connection to the solenoid which was fabricated by brazing several pieces together. Since that time, every effort is made to make lead spurs from a single copper plate which is formed and gun-drilled to form the coolant passage. Connection brazes, therefore, are made away from the region of discontinuity.

• Initial reliability of the PBX-M in-vessel passive coil system was less than expected for several reasons.[2] Many of the passive coil electrical insulators failed. Failures are thought to be due to voltages generated during rapid plasma disruptions which resulted in arcing across the polyimide insulators. Being an organic material, such arcing results in surface damage which then will continue to degrade. The fix involved replacing the polyimide bushing with ceramics and increasing the tracking path lengths. A second problem involved arcing along the line of sight in the direction of the toroidal field over rather long distances. These problem areas were resolved by installing inorganically bonded mica sheets to interrupt the lines of sight. The third problem involved excessive forces generated by currents unexpectedly flowing in supports. Originally each pair of passive coils were hard-grounded at a single point to the vacuum vessel. It is believed that plasma halo created a second connection which then permitted high currents to flow in the supports, which are immersed in the TF field. This problem was rectified by replacing the hard grounds by current-limiting 500 ohm resistive grounds.

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• The TFTR TF coils have had several instances of water leakage within the TF coils. The cause of all leaks has not been determined, but at least two are due to cracks in the wall of the oval copper tubing which is brazed into the edge of a TF coil turn. All were repaired in-situ by sealing the leaks with epoxy. Although it is not possible to perform a compete analysis at this time, TFTR's leak experience, coupled with those of JET, JT-60, and PBX-M point out the need to use extreme caution in the design, fabrication, and quality control of coolant details. Probably the best advise is to absolutely minimize the number of joints in a flow path and to configure them as much as possible for inspection and maintenance.

• Several of the TFTR bus bars failed pre-operational electrical tests during its initial commissioning. The problem was later found to be insufficient curing of the B-stage insulation by the supplier which made them susceptable to moisture absorption. This points out the need for stringent quality control and testing, even if it requires additional test equipment in the field.

• The initial bus bracing on TFTR had to be supplemented since that originally supplied were insufficient for operational and worst-case forces due to fields generated by the bus bars themselves and fields from the magnets. This points out the need to keep all elements of a magnet system in proper focus, even seemingly less critical "utilities".

• The TFTR coil cases consist of inner and outer rings and two bolted side covers. Each case has ~ 900 bolts which fasten the side covers to the rings. Some of these bolts have a tendency to loosen, especially in the higher stressed inner leg regions. The prevalent belief is that insufficient preload in the bolts allow them to loosen in service. This points out a need to either use extreme care in design or to provide locking means which do not depend on preload.

• The TFTR OH solenoid "spool" is held in position by brackets bolted to the TF coils. A field design change resulted in removable shims machined to locate the solenoid rather than the original one-piece bracket which was to be custom machined. In the new design, frictional forces were to restrain the shims. However, the shims tend to move during operation, requiring periodic re-positioning and tightening. This points out the need to be careful when making design changes that the original design considerations are still accounted for.

Good Magnet Design and Fabrication Practices:

Outlined below are the key factors in design and fabrication which have been developed or adopted over the years.

Metallic Materials: In selecting materials, published data is sometimes acceptable as a starting point but testing with sufficient depth and breadth to accurately characterize the material is necessary. Often the data in literature is for sizes or conditions which are not applicable to a tokamak. Materials researchers and potential suppliers should be involved early in the design process to give input concerning manufacturing limitations, material variation, potential for improvements, practical constraints such as shipping methods, etc.

Insulation: [3; 4] The electrical insulation is one of the most critical items in a magnet since it performs both mechanical and electrical functions. Mechanically, all electromagnetic loads generated within the magnet must be transmitted through the insulation to adjoining turns and structure. Electrically, it must guard against electrical breakdown turn-to-turn and turn-to-ground. As in the case of materials, testing of the proposed insulation system is required to determine its suitability since its capability is very strongly a factor its operating environment (radiation, temperature, pressure, etc.) and how it is applied. The materials most often used includes combinations of Mylar, Kapton, epoxy, and fiberglass. Both B-stage (resin pre-impregnated fiberglass cloth which is partially cured) and vacuum-pressure impregnated insulation systems have been successfully used in a number of applications. Vacuum-pressure impregnation (VPI) is much more difficult and costly, but is generally the best choice for magnets where electrical breakdown in voids is a major consideration since, when properly executed, it is virtually void-free.

When choosing the fiberglass cloth for VPI systems, the S-glass (structural) variant is generally chosen over the E-glass, (electrical) version which contains boron and becomes activated in radiation environments. The glass cloth is usually purchased with a coupling agent such as silane applied to increase epoxy wetting.

It is necessary to properly prepare the copper surfaces if bonding is required. Often the structural performance of the magnet demands turn-to-turn bonding so it structually behaves as a monolythic structure. Surface preparation generally involves degreasing, grit blasting, and application of epoxy primers to the freshly deoxidized copper surfaces.

To minimize variations in voltage stress in the insulation, a conductive paint is applied over the coil which is graded to a semi-conductive paint and finally an insulating length at the lead terminations.

Design Standards: At present, there are no formal standards regulating magnet design. In earlier designs, other design constraints such as the need to match system resistance to existing supplies or temperature rise limitations due to water cooling considerations generally resulted in modest stress levels. Next generation machines, however, are pressing the design boundaries and can benefit from standards. Using standards, even if they are in an evolutionary stage, takes advantage of collective wisdom and provides a formalized base on which to build. Magnet standards which address both the mechanical and electrical aspects of a design can be important in improving magnet reliability.

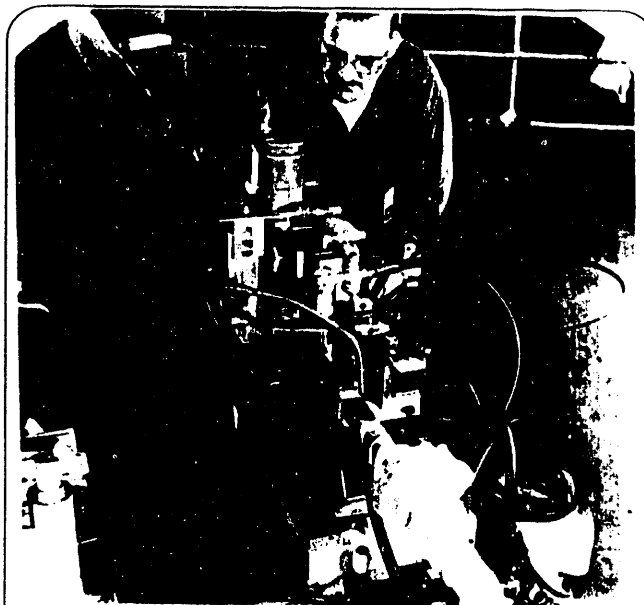

Figure 1. Induction Brazing Fixture

Copper Joining Methods: For non-heat treatable copper alloys, silver brazing with induction heating is used to join turn lengths. Whenever coolant flows through the brazed joint self-fluxing alloys (usually BCuP-5) with no additional external flux is used. Induction heating with closed-loop infared feedback is used for repeatability. Figure 1 shows a brazing fixture in use. Water-cooled chill blocks are incorporated into the fixture to minimize the heat affected zone. The joint configuration of choice at PPPL for internally cooled conductors is a butt joint with a counterbored copper sleeve. Silver is pre-placed at the butt joint and each end of the sleeve. This ensures a degree of redundancy on the coolant passage, since the butt joint should in itself be pressure tight with the brazed sleeve as a back up.

The joint testing method developed for TFTR has been adopted as the "standard" method. The internal passage is pressurized with helium and "sniffed" with a mass spectrometer while the joint is hydraulically stretched, both to partially restore the yield point of the heat affected zone and to stress the joint. The in-line joint stretching apparatus is shown in Fig. 2. Resistance measurements across the joints have been found to be ineffective. For heat-treatable copper joints such as those proposed for BPX welding followed by heat treatment is planned. This method is described in detail in another paper.[5]

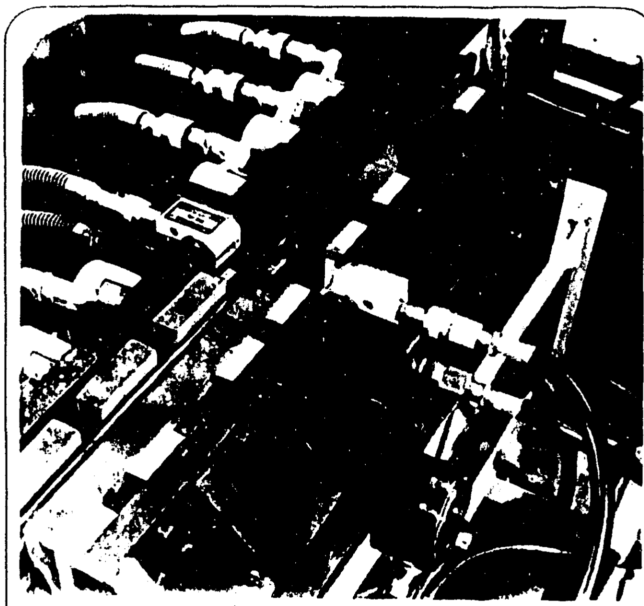

Figure 2. Brazed Joint Hydraulic Test Fixture.

Coil Winding Methods: [6] Uniform application of tension during winding is necessary for a tightly wound coil. Friction breaks acting through cables were used for early coils: a hydraulic tensioning unit developed for TFTR, provides much more uniform tension and is preferred.

Turn-to-turn transitions: Hydraulically formed turn to turn transitions are used, with the brazed or weld joints located some distance from the transitions and staggered in locations so as to distribute discontinuities.

Leads: To avoid brazed regions in a lead transition area, the transition piece is cut from a plate of copper which is then gun drilled to form the water passage and then formed, as shown in Fig. 3. The TFTR PF coils were fabricated and vacuum pressure impregnated with relatively short lead stem extensions. After being transported to the Test Cell, the remainder of the lead stem was joined to the stem so as to form a monolythic coil/stem assembly.[7] This design moves the position of the first non-integral joint outside of the main of the tokamak into a region of lower field and where access is much better. The lead joining procedure, shown in Fig. 4, involved brazing, insulating, and VPI.

Testing: Testing during fabrication generally involves copper hardness, dimensions, conductivity, leak testing of joints, pre-impregnation resistance and turn to turn tests Post VPI tests include turn to turn electrical impulse tests, megger, DC hipot, AC hipot and corona, and loss tangent measurements. A subset of these tests is generally performed after major shipping or installation procedures.

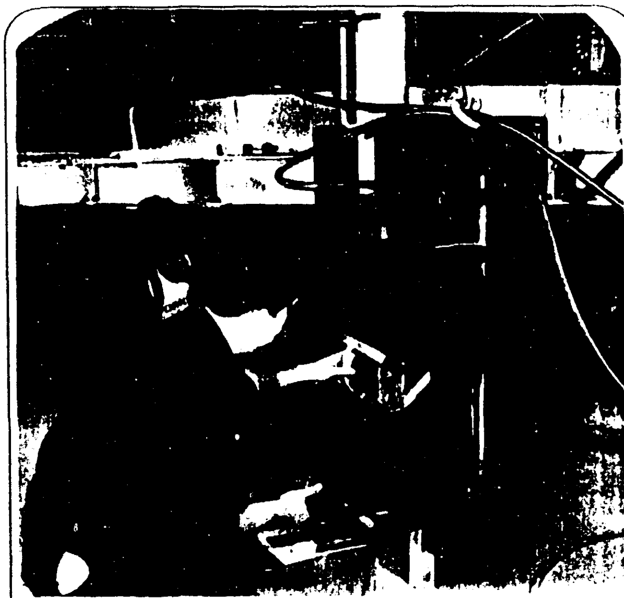

Figure 3. Forming of a Lead Transition.

Bus Systems: Bus reliability is found to be improved if belleville washers are used to assure adequate and stable joint pressure and silver plating is used to assure stable and low joint resistance. Adequate analysis and bracing for worst-case operation is necessary; the scope and impact of this design task is often underestimated and made more difficult by its usually being among the last to be completed. Maintenance practices which have been found to be helpful include using thermal stickers to permit monitoring peak joint temperatures during operation, using low resistance bridge measurements for both initial and maintenance checks of joint resistance, and performing periodic bolt torque checks. Allocation of sufficient space for maintenance of bus systems during initial design, and preservation of this space as the design matures and features and equipment are added deserves high priority.

Figure 4. TFTR PF Lead Splicing.

Summary

Magnet engineering experience and the availability of sophisticated engineering tools has made in-magnet failures rare. Field experience has shown the majority of reliability issues to be associated with external details of the magnet systems, such as utilities and supports. Overall system reliability can be improved by extending the level of care used in design and fabrication of the magnets themselves to these other areas and by incorporating effective quality control and quality assurance throughout the project.

Acknowledgements

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