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Lessons Learned During the Manufacture of the NCSX Modular Coils

James H. Chrzanowski,Thomas G. Meighan,
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James H. Chrzanowski,Thomas G. Meighan,
Steven Raftopoulos and Lawrence Dudek
Princeton Plasma Physics Laboratory
PO Box 451, Princeton, NJ 08543

Paul, J. Fogarty
Oak Ridge national Laboratory
P.O Box 2008, Oak Ridge, TN 37831

***Abstract*—the National Compact Stellarator Experiment's (NCSX) modular coils presented a number of engineering and manufacturing challenges due to their complex shapes, requirements for high dimensional accuracy and high current density requirements due to space constraints. Being the first of their kind, these coils required the implementation of many new manufacturing and measuring techniques and procedures. This was the first time that these manufacturing techniques and methods were applied in the production of coils at the laboratory. This resulted in a steep learning curve for the first several coils. Through the effective use of procedures, tooling modifications, involvement and ownership by the manufacturing workforce, and an emphasis on safety, the assembly team was able to reduce the manufacturing times and improve upon the manufacturing methods. This paper will discuss the learning curve and steps that were taken to improve the manufacturing efficiency and reduce the manufacturing times for the modular coils without forfeiting quality.**

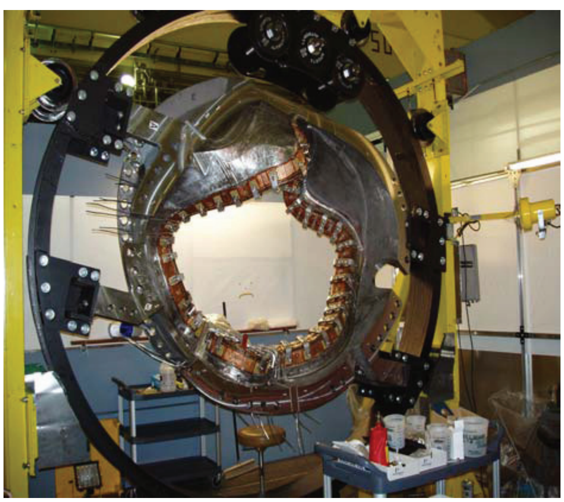

Figure No. 1 Finished Modular Coil

I. Introduction

A total of eighteen modular coils [Fig.1] were successfully manufactured for the NCSX project. These coils introduced a number of challenges due to their complex shapes, requirements for high dimensional accuracy and high current density requirements due to space constraints. There were a number of lessons that were learned during the manufacturing and planning phase that could be transferred to other manufacturing projects.

Every new project should begin with a good engineering design. A project that is well defined and engineered will minimize the numerous problems and obstacles that will likely occur during manufacturing. In the case of the modular coils we found that there were a number of "key" elements that were essential to manufacturing success. Areas of improvement that could be incorporated into future jobs were also identified. These are outlined below.

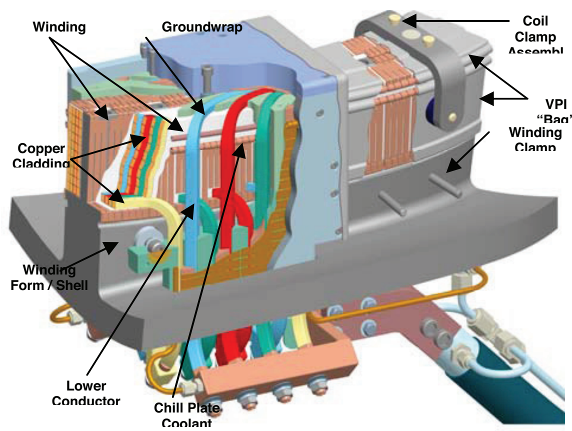

Figure 2- Modular Coil Cross-Section

II. R&D Activities

The R&D phase provided an opportunity to develop an understanding the materials that were to be used for the modular coils as well as to develop the processes that would be required to manufacture the coils. A significant amount of time was allotted for this purpose. Nearly 3 years was spent on the R&D and setup of manufacturing facility; this included manufacturing a prototype coil that verified the manufacturing processes and procedures. The information and data obtained from the R&D tasks were then used as the basis for developing the manufacturing processes and preliminary manufacturing procedures. Several of the most significant R&D tasks are described below.

A. Selection and verification of epoxy resin, conductor and insulation schemes

R&D activities were performed to verify that the selected resin system and insulation scheme was acceptable. In addition, a great deal of time was spent with the conductor manufacturer developing and down selecting the details of the copper rope conductor that met the modular coil requirements.

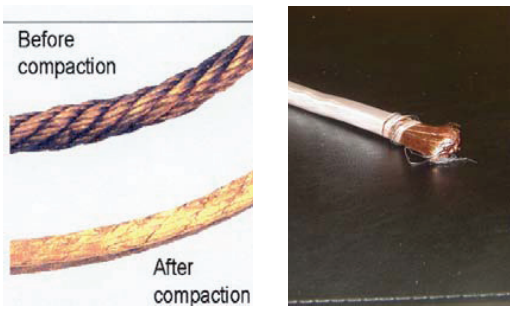

Figure No. 3- Compacted Rope Conductor

B. Identifying Tolerance Control Issues

The primary tolerance control issues had to do with the copper rope conductor. The rope conductor was selected to accommodate the complex geometry of the modular coils. However, the rope conductor has a tendency to change dimensions during handling. This fact along with the issues associated with keystoning of the conductor during winding was of particular concern because of the tight tolerance requirements and the need for dimensional control. Following extensive R&D it was determined that the copper rope conductor had benefits in regards to tolerance control. After the conductor is wound onto the winding form the coil is carefully measured with a multi-link CMM (Component Measuring Machine). After analysis and comparison with other coils of a similar type, the technicians are provided with information to guide tightening of clamp bars (refer to Fig. 5) to reshape the coil cross sections as required to meet requirements and make all coils of a given type similar. in dimensional characteristics. This similarity provides "stellarator symmetry" which reduces the effect of errors. This information provided the NCSX program with the controls necessary to maintain the tight tolerance of the current centers.

In addition, the selection of the metrology equipment and metrology techniques were developed during this phase.

C. Development of a VPI (Vacuum Pressure Impregnation) Process

A VPI process was developed that ensured full impregnation of the copper rope conductor and insulation using the selected resin system. A series of specimens were processed to verify the VPI process and to provide specimens for mechanical and electrical testing.

Figure 4 shows the results of a successful VPI of the copper rope conductor. Note the complete penetration of epoxy between strands.

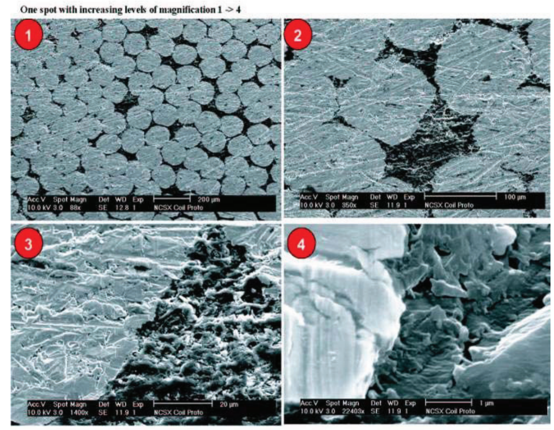

Figure No. 4- Electron Microscope Photo of Resin Filled Conductor

D. Development of Winding and Metrology Methodology

The R&D phase provided a basis for the development of the manufacturing processes and tooling design. The coil winding methodology was determined and included such items as the handling of the copper rope conductor; brazing techniques for the leads; installation of the copper chill plates and groundwall insulation. These techniques and processes were verified with the fabrication of a prototype coil [Figure 5] that included the manufacturing processes that would be used in the MC production.

The winding methodology continued to be refined throughout the manufacturing process. The technicians provided recommendations and improvements to the processes. PPPL had an incentive program "SPOT AWARD" that was used to encourage the technician force to find improvements that would help reduce cost and schedule.

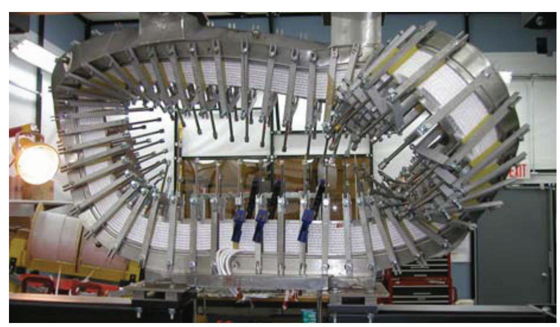

Figure No. 5- Prototype Coil "Twisted Racetrack Coil"

III. PROCEDURES AND METHODOLOGY

Procedures provided details of the manufacturing processes with appropriate Q.C. hold points and approvals. They also provided pertinent safety information including cautions and identification of the appropriate personal protective equipment to be used for various operations.

Throughout the manufacturing cycle the workforce provided input and recommendations for improving the procedures. The procedures were updated and revised often to capture all changes or improvements to the processes.

IV. SAFETY

Safety is an important element of the PPPL culture and was incorporated in all aspects of the development program and carried over to production of the Modular Coils. Bi-weekly safety meetings were held with the manufacturing staff discussing safety topics and equipment both job specific as well as home safety. During the entire 6 year program that included both R&D and production, there were no loss time accidents. The safety environment that surrounded the Modular Coil program helped eliminate injuries and schedule delays.

V. LEARNING CURVE

There was a steep learning curve during the modular coil manufacturing. This was partially due to the multiple work stations and inexperienced coil winding crews. Most of the technicians had little or no knowledge in coil production. These skills had to be taught to the entire team. In order to meet the schedule demands there were multiple winding stations (3) that were operated on a two shift basis. With a peak work force of 18 technicians and an initial staggered station startup, the teams did not become efficient until the completion of the 3rd. modular coil. The first modular coil took nearly 6200 man-hours to complete. However, this time was reduced to 3400 man-hours once the teams reached their full stride.

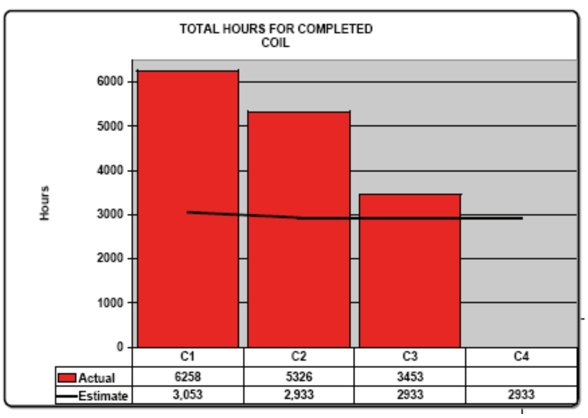

Figure No. 6- Modular Coil Manufacturing Learning Curve

Extensive training was provided to the technicians. In addition continual improvements in the manufacturing processes and procedures contributed to the reductions in hours.

One of the most important contributing factors for the steady reduction in manufacturing times was personal ownership of the modular coils that the teams were given. Each work station and team was assigned a modular coil that they followed through to completion. This helped to generate competition between teams and instilled personal pride in their workmanship. Another positive outcome was an improvement in the quality of the modular coils.

VI. VACUUM-PRESSURE-IMPREGNATION [VPI]

In general the “bag mold” technique and the VPI (vacuum-pressure-impregnation) operations went smoothly. The “bag mold” provided a simple method for providing a vacuum boundary of these coils with their complex geometry during the VPI process. The concept worked well, but was sensitive to damage (small cuts) during the application of the mold causing unsuspecting leaks once the bag began to expand. These leaks were satisfactorily addressed during the VPI process. The mold, though delicate, was a reasonably priced method for providing a vacuum tight mold around a complicated geometry. A detail description of the ”bag mold” can be found in the proceeding from the 22nd. SOFE, in Albuquerque, NM

Figure No. 7- “Bag Mold” Under Vacuum

The epoxy filling (VPI) of the coils went well. The modular coils were VPI’d in the vertical position with adequate fill points to accommodate the complex geometry.

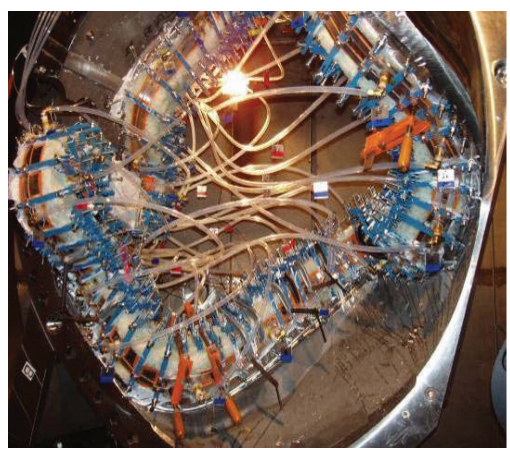

Figure No. 8- MC in Autoclave during VPI process

VII. Areas of Improvement

There were a number of areas where improvements or planning changes could have resulted in a reduction in manufacturing times and perhaps an enhancement of design.

A. *Metrology*

Due to the tight tolerance requirements (+/- 0.5 mm current center), metrology played an important element in the manufacturing process. However, the metrology needs were under-estimated. The hours allotted for measuring the coil positions and re-positioning the coil bundles/turns were significantly underestimated. In addition the metrology teams were understaffed and the equipment was often unreliable. Both hardware and software issues were experienced. Similar type projects in the future must be careful to adequately budget for metrology needs.

B. *Inadequate Manpower*

As noted in the metrology section, inadequate manpower was a serious issue. This was also true during the early design phase of the project. The lack of completed design studies and detail drawings resulted in a ripple down effect throughout the manufacturing phase. Often product drawings were not completed in reasonable time causing delays in production.

During the fabrication of the stainless cast winding forms, the coil to coil clearance studies had not been completed. This resulted in the winding forms being sent to NCSX prior to the completion of the any additional material removal as a result of these studies. The work had to be completed at PPPL but was not included in our schedule and budget estimates. These activities would be been less expensive if performed at the vendor during the initial machining operations.

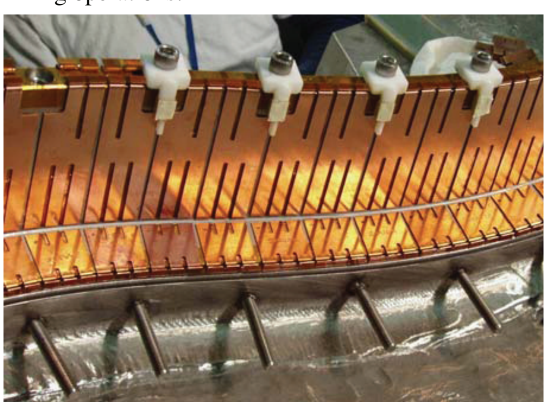

Figure No. 9- Copper Chill Plates in Position

C. *Coil Cooling System Improvements*

The modular coil cooling system design that was selected had a significant number of components that had to be handled and installed. There were over 1500 individual chill plates on each modular coil that had to be manufactured, prepared and installed. Further studies may have resulted in a different cooling system design that had fewer components and may have played an important role in reducing costs and schedule.

VIII. Summary

The NCSX Modular Coil program had numerous technical challenges that had to be addressed and overcome. A total of eighteen modular coils were successfully completed including (1) coil that was fully cold tested at its operating currents. The coils also met the current center tolerance requirements of +/- 0.5 mm. Along with all of the technical achievements, the modular coil R&D program and manufacturing activities spanning 6 years were accomplished without a single time loss accident. Even though the NCSX Project was cancelled it is our hope that the technical and project lessons that were learned will benefit future projects.

Acknowledgment

The author would like to thank the entire NCSX team at PPPL and ORNL for their contributions to this work. A special note of thanks goes out to the lead technicians and Quality Control team that provided the oversight and hard work to ensure that the coils were completed with the highest level of quality.

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov