Modular Coil Winding Forms, the Twisted Racetrack Coil R&D, and Modular Coil Winding Process

The modular coils are formed by winding and potting flexible cable into cast and machined modular coil winding forms (MCWF). These are being fabricated by EIO under a fixed price contract. The first of these forms has been delivered to PPPL and is in the winding process.

The NCSX winding team has moved expeditiously on the R&D of the twisted racetrack coil (TRC) to resolve outstanding issues with conductor placement, clamping, potting and cooling raised in previous reviews. This had many positive impacts on the winding process which as just begun on the MCWF and confidence in the performance of the completed modular coils.

Findings

The first modular coil winding form has arrived and with some modest in-house work is now ready for winding. The patterns for all three MCWF's are complete. The foundry has cast 6 of the type "C" (the most complicated) castings and two of the type "A". The material for the castings, "Stellalloy" has been fully characterized and exceeds all needed requirements.

The critical path for the MCWF production is the machining required to clean up the casting and produce the winding surfaces for the flexible conductor. The first MCFW took 26 weeks to machine and arrived 3 months late. This was due to a large number of required setups on the machine tool and significant programming changes needed to avoid tool/form interferences and generate the complicated needed shape. The second and third forms are in process with expected delivery at the end of November, and December 29, 2005, respectively. Some improvement in the machining rate is being achieved on the second and third castings, but it is still far below that projected in the contract schedule. Good relations appear to be maintained between PPPL and the vendors and every effort is being made to speed up the MCWF machining. With the delivery of the next two forms coil winding can continue at PPPL on those articles without impact from the MCWF delivery.

Costs have been held to date at contract levels, with only a minor revision (~2%) due to NCSX initiated changes for stress relieving of the casting and some winding details such as penetrations. The biggest risk appears to be schedule due to the excessive machining time required. Even so, the project has assessed delivery with estimates more conservative than those now provided by EIO and determined that the critical path now winds through the coil winding process.

Methods have been developed to accurately place and hold the flexible cable conductor against the winding form. As a result of this experience, and in accordance with a previous review, they have decided to eliminate the shimming from turn-to-turn as previously considered and chosen to go with a "go/no-go" gauging type system for turn

placement within a prescribed winding envelope. This has the benefit of faster winding, but more importantly, the ability to add an additional layer into the winding pack resulting in reduced current densities and a 20% reduction in the heat deposited in a discharge.

Concerns about the coil cooling method have been addressed and the design simplified from that presented at the FDR resulting in a more workable design with easier installation at winding time and impact on clamping. The cooling has been tested on the TRC with equivalent I**2t pulses for similar heat deposition. Tests showed sufficient thermal conductivity to remove the heat in the envisaged 15 minute cycle time with only a small amount of ratcheting (approximately 20C). No extensive thermal cycling tests were performed. This modified design is projected to add roughly 300 person-hours/coil to fabrication time.

A problem encountered with conductor motion in the outer turns when clamps are removed for installation of the ground wrap has been resolved by a technique of 'lacing', or fixing of the winding locations with strips of glass/epoxy at critical spots.

A revised method of cocooning (or bagging) of the coil for epoxy impregnation has been developed which substantially reduces the time needed for this step in the fabrication. The impregnation has been tested on the TRC and subsequent examination through cuts in the TRC show complete impregnation and that there are no dry spots. A resin rich area was identified and a method to prevent this is in hand.

Increased costs have been identified for groundwrap and metrology from experience on the TRC, also resulting in increased fabrication time/coil. The schedule planning as it stands has allowed an adequate time for the fabrication of first articles of a given type, with a modest credit in subsequent articles for the learning process. It is possible that more significant improvements in the speed of fabrication will be achieved as the crews develop experience, potentially offsetting the envisioned increased costs.

Torsion and bending tests of material properties of the copper/glass/epoxy matrix was completed on beam samples showing values sufficient for structural modeling of the coil/support system for over 600,000 cycles. Tensile tests in the TRC showed also showed sufficient properties.

A workable fixture has been developed for positioning the coil during the winding process permitting access to both sides of the coil speeding up the winding process and minimizing the lifts/moves needed of the coil/form.

Two winding stations in 'clean' rooms have been set up so that winding can proceed on two coil modules concurrently. The first modular coil using the single delivered modular coil winding form was in the fabrication process.

The plan is to run both lines for two shifts per day to speed up the modular coil winding process.

Comments

The committee finds that the NCSX project has made significant progress in identifying and resolving many of the complex fabrication steps required to wind and VPI the MC's and we commend them for this achievement. The main outstanding issue is the total amount of time required to fabricate each MC, since the project critical path is now determined by this activity. The committee feels that the project has made a realistic and probably conservative estimate for MC fabrication and agrees that the two winding lines and double shifts are necessary to maintain the 5 month project float. The project is developing contingency plans to maintain or accelerate MC winding production should these activities take longer than presently scheduled. This schedule contingency includes adding a third winding line first, followed by weekend shifts if necessary. The committee feels that experienced engineering oversight of these MC fabrication activities is critical to achieving the schedule milestones while preserving the critical important fabrication quality. Presently planned engineering staffing is adequate but not excessive. Project management should continue to ensure that qualified engineering personnel are available to maintain high quality oversight for the extended MC manufacturing period without excessive stress of personnel, and especially if a third winding line becomes necessary to maintain the schedule.

There is particular concern with the actual manufacturing time for machining and delivery of the remaining MCWF. The project personnel have worked very well with EIO to ensure achieving the tight tolerances required on the machined MCWFs. The committee is concerned that the overall acceleration of delivered pieces may not materialize because of the highly complex nature of the machining operations. It is possible that the critical path may alternate between MCWF delivery and coil winding, although at this point it is clearly on the winding line.

Recommendations

Continue to place high priority on MC winding activities with the goal to minimizing fabrication time while maintaining high quality.

Continue to work proactively with EIO for delivery of the MCWFs to the most recently developed schedule.

Closely re-examine the schedule and costing for the modular coil systems after the fabrication of the first three articles and provide an interim report to DoE on these results and progress with all aspects of the modular coil fabrication.

Findings (VVSA)

Substantial progress has been made in the VVSA including completing the R&D and completion of all production processes for the panel stampings, including development of production welding procedures and port boring steps. To date panels for 2 of 3 120° segment shells have been been welded into their final shell configuration. Ports are being fabricated and port holes remain to be bored. NCSX staff will assist MTM with developing leak checking procedures. On site QA support is given by DCMA. Excellent geometric results have been confirmed using Verisurf® software, with only a few, non-critical areas outside the tolerance specification. This will not be an interference problem for assembly.

The schedule has slipped about 1 month from the baseline but well within the float allowance. The subcontract cost increased about 10% from the original price due to need for new forming dies and new flanges made from material with lower permeability. But since most of the process development has been completed there appears to be little risk of cost growth.

Excellent communications and working relationships has been established between NCSX project staff and MTM, and it appears that this task should proceed as scheduled and budgeted, pending confirmation of port welding and leak checking process finalization.

Comment (VVSA)
The review committee supports the projects decision to provide leak checking equipment and personnel to establish and supervise MTM leak checking of the VV segments with ports installed.

Findings (Conventional Coils)
The original plan was to have all TF and PF coils manufactured by industrial vendors. . Based on this prior experience and perceived lack of attention to production quality, the NCSX project performed a "Make vs. Buy" study. They concluded that there is no cost difference when oversight costs, estimates of GA and vendor profit were factored in. One of the main concerns was potential risk associated with manufacturing quality, because, if a TF coil fails in service it would cause severe disruption to machine operations if it needed to be replaced. The intention, at this time, is for the NCSX project to wind at least the first TF coil, but some other options are being investigated, including the possibility of having the TF (and possibly the PF) coils fabricated in China by the ASIPP in Hefei.

The project has established a TF coil winding line and begun setting up the clean room and winding table. All tooling has been designed except for about 50% of the VPI molds. Much of the tooling has started fabrication in PPPL facilities. The estimate for the TF coil fabrication was increased by $880k. The project has offset some of these increases through use of the NSTX PF1a coils and simplified trim coils.

Only a single bid was received from industry for the TF wedge castings. The quotation was significantly above the budget estimate. The project is reconsidering the tolerance and materials specification. Castings are not required until late FY06 so the schedule is not impacted yet.

Comments (Conventional Coils)
The committee feels that the project's concern about coil quality is legitimate, especially based on prior experience with the few US vendors still active in this area of coil fabrication. The main concern of the committee is whether the additional effort required to wind all 18 coils in house will overload the qualified personnel resources available to the project. The project has established the TF winding next to the MC winding lines and this should result in efficient use of shared oversight engineering personnel. **The availability of adequate oversight engineering personnel should be a factor in future decisions about adding additional winding lines, weekend shifts, or possibly winding the PF coils in house.** The issue of where the PF coils will be fabricated should be determined soon so that provisions can be made in the schedule, especially if it is determined they need to be wound in-house.

Fabrication of the TF and PF coils in China at ASIPP may be a credible, and even preferred option, if a suitable collaboration could be established. The IPP-Hefei has developed a significant in-house capability in coil fabrication and has just completed manufacturing of the entire superconducting magnet system for the EAST tokamak. This could lead to a significant cost reduction in conventional coil fabrication.

The high quoted cost from a single vendor for the TF wedge castings is also a significant concern. Further effort should be given to understanding the reasons for this situation and continue efforts to modify the choice of alloy and manufacturing tolerances to bring the cost lower.

A credit for $154K has been taken for simplifying the design of the trim coils, although no further design details were presented in this review.

Recommendations (Conventional Coils)
Seriously pursue the option of having all TF and PF coils fabricated in China leading to a decision by 2nd quarter 2006. Because of the uncertainty with the winding time required for the MCs, the committee does not recommend that additional PF winding be taken on as an in-house activity.

Investigate further whether it might still be feasible to have the TF and PF coils fabricated in industry with high quality if sufficient oversight personnel can be provided at the necessary level.

Apply further effort to reducing the cost of the TF wedge castings, so that procurement can proceed without schedule impact.

Analyze the modified design of the correction coils to insure adequate performance for plasma quality and confirm the cost reduction credit..

Findings (Field Period Assembly)
Significant progress is reported in Field Period Assembly (FPA) including design work on VV prep stations, half period assembly tooling and spherical seat locators. R&D activities include a demonstration for testing the alignment of the spherical seat assemblies and measurement of their position using the Leica laser metrology system. There was a cost increase of 655K identified through required assembly hardware not in the rebaselined budget.

A rather complex and relatively expensive mechanical assembly tool has been designed to install the MC over the VV. But a clever suggestion was made to try to use the overhead crane as the primary tool to perform this assembly process. A demonstration of this technique was performed using the overhead crane and hand assisted assembly. It was concluded that this could be a viable and very cost effective solution for performing this critical assembly step.

Comments (Field Period Assembly)
The committee commends the project on their ingenuity in developing the crane plus hand assist method for FPA. This could result in significant cost savings to the project.

Recommendations (Field Period Assembly)
Pursue further the development and refinement of the assembly procedures using the crane method for installation of the MC over the VV sectors. Pay particular attention to safety in developing these procedures due to the heavy lifts and critical nature of the procedure.