Princeton Plasma Physics Laboratory

PPPL-4122 PPPL-4122

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October 2005

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

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P. Heitzenroeder[a], T. Brown[a], G. Neilson[a], F. Malinowski[a] , L. Sutton[a], B. Nelson[b], D. Williamson[b], N. Horton[c], B. Goddard[d], J. Edwards[e], K. Bowling[f] , K. Hatzilias[g]

[a]*Princeton Plasma Physics Laboratory, Princeton, NJ*

[b]*Oak Ridge National Laboratory, Oak Ridge, TN ;* [c]*Energy Industries of Ohio, Independence, OH;* [d]*C.A. Lawton Co., De Pere, WI;* [e]*MetalTek International, Pevely, MO;* [f]*Major Tool and Machine, Inc., Indianapolis, IN;* [g]*3D Scanco, Lawrenceville, Ga.*

Abstract— The production phase for the NCSX modular coil winding forms has been underway for approximately one year as of this date. This is the culmination of R&D efforts which were performed in 2001-4. The R&D efforts included limited manufacturing studies while NCSX was in its conceptual design phase followed by more detailed manufacturing studies by two teams which included the fabrication of full scale prototypes [1]. This provided the foundation necessary for the production parts to be produced under a firm price and schedule contract which was issued in September, 2004. This paper will describe the winding forms, the production team and team management, details of the production process, and the achievements for the first year.

Keywords-Coils; production; fabrication.

I. INTRODUCTION

NCSX is under construction at the Princeton Plasma Physics Laboratory as a joint project of PPPL and the Oak Ridge National Laboratory. It is the first of a new class of stellarators known as compact stellarators. Compact stellarators are expected to retain the steady state operational characteristics of traditional stellarators but at a much smaller size – both key elements to the successful development of fusion. NCSX is designed with an aspect ratio of 4.4; a traditional stellarator typically has an aspect ratio of ~10[2]. NCSX is shown in Fig. 1. It utilizes LN_2 cooled copper magnets, has a major radius of 1.4 m, a magnetic field of 1.2-2T, and a pulse duration of 0.3-1.2 S. First plasma is scheduled for July, 2009. The complex magnetic field required to produce the field in NCSX is generated by a set of (18) modular field coils. The modular coil system is comprised of six each of three different types of modular coils, as shown in Fig. 2. Each machined winding form weighs ~2500 kg. The modular coils are made by winding flexible, compacted stranded cable directly on the cast-and-machined stainless steel winding forms. The completed windings are vacuum-pressure impregnation with epoxy to bond them into a monolithic structure. Spring loaded clamps hold the windings on the winding form during operation while still allowing for thermal expansion. The current centers of each modular coil must be located within +/-1.5 mm. This tolerance is allocated equally between the winding form, the winding, and assembly.

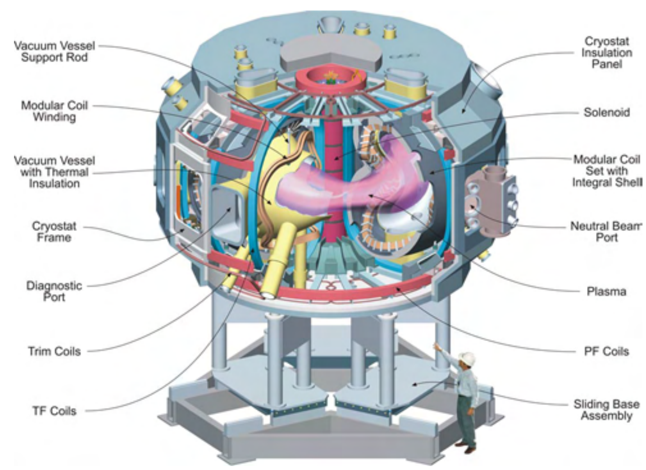

Figure 1. The NCSX Device

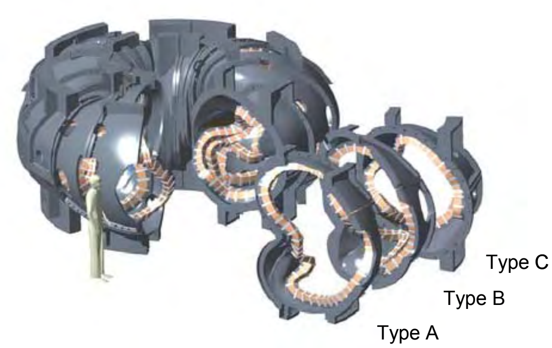

Figure 2. The Modular Coil System

II. THE PRODUCTION TEAM AND TEAM MANAGEMENT

Energy Industries of Ohio, (EIO), a 501c3 nonprofit corporation with the charter to participate in and promote development and deployment of scientific technologies and innovative concepts to assist Ohio's energy producers and energy intensive industries, is the prime contractor for the production phase of the NCSX Modular Coil Winding Forms providing the overall program management, contract and financial management and task coordination. EIO is supported by a team of experts with the technical capability and experience to produce the winding forms, including the pattern maker - C. A. Lawton Company, the foundry - MetalTek International, and the machine shop - Major Tool and Machine. Under subcontracts to EIO, these team members are empowered with full responsibility and accountability for their specialized performance. This team structure offers significant benefit to PPPL, including a single point of contact for all matters, superior program and Government contract management, objective technical and quality oversight that is customer, not profit, driven and a production team comprised of the best in their field.

The challenge with such an approach is to balance good communication with efficient performance. EIO is tasked with delivering to PPPL a steady stream of timely and accurate information about production activities, while minimizing the associated administrative burden on the partners. EIO must ensure that all partners have access to each other for technical and quality discussions, at the same time maintaining contractual boundaries. To accomplish the management task, EIO utilizes a combination of phone calls, personal visits, written reports, e-mail and on-line updates to obtain and share information, offering round the clock access to partners to accommodate varied schedules and urgent requirements. Initially, EIO attempted to implement a customized software program to track all on-line correspondence and provide a forum for real-time updates and access to shared data. Theoretically, this was the ideal management tool, but practically it did not meet the goal of minimizing the administrative burden on the partners, as the system required a level of user training and dedication that was impractical to implement in the fast-paced, day to day operations of a diverse production team. EIO replaced this single system with more flexible tools including a centralized ftp site which retains the historical document archive and provides the forum for sharing drawings, plans and technical reports. Coupled with this web based tool, EIO utilizes a weekly report to assign and track action items and holds a regularly scheduled weekly telecom with PPPL to discuss Quality Assurance matters and other technical and administrative items that arise during the week. Subtier team members are included in this meeting on an as-needed or requested basis so as not to unduly tie up their schedules, with EIO using targeted e-mails and phone calls to secure necessary input. The result is a system that provides coordinated, yet flexible, interaction between PPPL and the EIO team to ensure rapid response to requests for information, immediate resolution of problems and satisfactory fulfillment of contractual obligation

III. THE CASTING ALLOY

The winding form casting alloy must have low magnetic permeability ($\mu<1.02$) both in the base metal and welds, and good welding characteristics to facilitate weld repairs to be made. Preferably, it should be able to develop the required mechanical properties without the need for water quenching to avoid thermally induced distortion. Since standard alloys could not meet all of these requirements, a custom stainless steel alloy, named "Stellalloy", was developed as part of the R&D activities by MetalTek International. Its chemical composition is given in Table 1.

	C	Mn	Si	Cr	Ni	Mo	P	S	N
Min. %	.040	2.3	--	18.0	13.0	2.1	--	--	.24
Max. %	.070	2.8	0.7	18.5	13.5	2.5	0.035	0.025	.28

TABLE I. STELLALLOY CHEMISTRY.

The specified mechanical properties are compared to those actually achieved for the first four castings in Table II. The achieved properties exceed specifications, especially at 77K. This provides additional design margins since the peak electromagnetic loads occur with the winding forms cold.

TABLE II. SPECIFIED VS. ACHIEVED PROPERTIES FOR THE FIRST FOUR CASTINGS

At 77 K		Casting Identification			
Property	**Specification**	**C1**	**C2**	**C3**	**A1**
Elastic Modulus	144.8 Gpa	160.9	176.1	171.9	175.8
0.2% Yield Strength	496.4 Gpa	678.5	642.6	669.5	670.9
Tensile Strength	655 Gpa	1174.0	1129.6	1124.8	1146.6
Elongation	32.0%	55.7%	54.3%	55.7%	56.0%
Charpy V – notch Energy	47.4 J	104.9	113.9	134.6	106.2

At 293 K		Casting Identification			
Property	**Specification**	**C1**	**C2**	**C3**	**A1**
Elastic Modulus	137.9 Gpa	159.5	156.3	148.9	149.4
0.2% Yield Strength	234.4 Gpa	241.9	252.1	263.8	252.6
Tensile Strength	537.8 Mpa	576.9	568.4	570.2	567.9
Elongation	36.0%	52.0%	53.5%	52.5%	53.2%
Charpy V – notch Energy	67.8 J	191.7	203.4	212.4	221.0

Fracture mechanics evaluations were made from specimens cut from the shell of a prototype winding form [2]. The results of these evaluations, shown in Table III, indicate that the winding form is capable of withstanding four times the number of full power pulses required by NCSX's Design Criteria at 215 MPa, which is the peak stress in the winding form, with initial flaws as large as 2 x 6 mm.

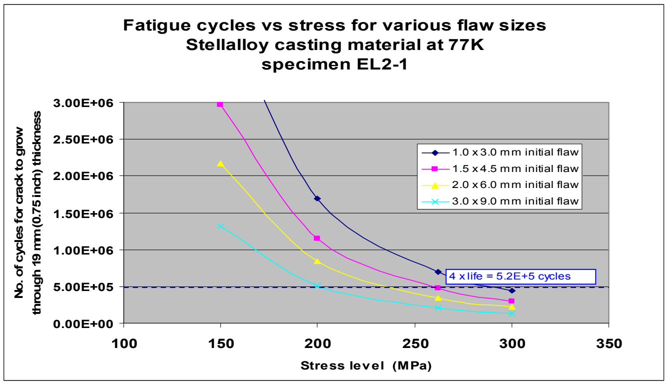

TABLE III. FATIGUE EVALUATION OF THE NCSX WINDING FORM

IV. PRODUCTION DETAILS

A. Pattern Design and Manufacture

In the sand casting process, molten metal is poured into a sand mold with internal cavities having the size and shape required to produce the part. The sand mold can only be used one time, since it is destroyed in the process. To assure that multiple castings can be produced which are replicas of each other, a pattern is used to produce the molds. The sand mold components are made by packing sand mixed with an air-cure resin in and/or around patterns. The basic process in developing a pattern is as follows:

(1) The solid model of the part is dimensionally adjusted to compensate for shrinkage as it cools from pouring temperature.

(2) Additional stock is added to the model for machining allowance.

(3) Flow/solidification analyses are performed based on the model developed above to determine mold details such as the number and placement of "risers" (molten metal reservoirs), "gating" (piping), heat sinks ("chills") and insulation. The goal of this process is to optimize the mold details in order to avoid shrink regions in the part. The result of an analysis for the Type C casting is shown in Fig. 3.

(4) The segmentation of the patterns is determined in consultation with the foundry

(5) CAD models are made of the pattern and mold.

(6) The patterns are contour-milled from mahogany (Figure 4).

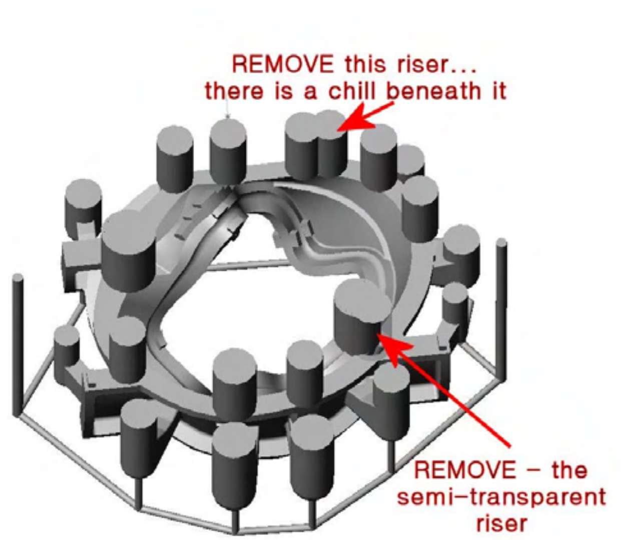

Figure 3. A Flow / Solidification Model for the Type C Winding Form

Figure 4. Contour Milling of a Paattern

B. Foundry Operations

The mold sub-assemblies (called core boxes) are made by packing sand mixed with an air-cure resin around the patterns and then removing the pattern after the resin cures, leaving the required cavity. The core boxes are then carefully assembled in a steel housing called a flask which holds the core boxes in their correct position and ensures that they do not shift during the pouring operation. For each NCSX casting, approximately 10,000 kg of pre-cast billets of argon oxygen decarburized (AOD) refined Stellalloy are melted in induction furnaces. Prior to pouring, each batch is analyzed and elemental corrections are made as necessary to meet chemistry requirements. During a casting pour, shown in Fig. 5, the molten alloy is simultaneously poured into the mold at three entrance points in approximately 1-1/2 minutes. Following cool-down, the flask is disassembled and the casting is "shaken out" (i.e. the mold is broken away). A casting shortly after shake out is shown in Fig. 6.

Figure 5. Pouring of a Castiing

Figure 6. A Casting After Shakeout

Each casting is solution heat treated and air cooled after removal of the risers and gating by arc burning. To verify the pattern and mold designs, both the pattern and the first casting produced is dimensionally checked by a photogrammetry/laser scanning process (Fig. 7). Visual inspections are performed per ASTM A 802/A802M; flaws are removed by grinding and weld repaired. Radiographic inspections are performed per MSS SP-54 to identify internal flaws. Those not meeting requirements are excavated and weld repaired. Magnetic permeability is checked at both the foundry and after machining. Each casting is stress relieved after all weld repairs are completed to dimensionally stabilize the part and to provide uniform properties for machining. Final foundry inspections include dimensions using a multi-link coordinate measuring machine (CMM) and a complete liquid penetrant inspection per ASTM A903/A903M.

Figure 7. Laser Scanning of a Pattern Component

C. Machining

Machining of the first winding form took about twice as long as initially planned due to the challenges presented by the complex geometry and the new alloy. Computer simulations of 3 and 5 axis CNC machining were performed to determine the reach and access of the milling machines during the planning stage. Machining simulations have a good track record of success; what was different in the case of NCSX is the extent to which the milling heads and cutters had to be extended due to its complex geometry. In some cases, machining head details which did not have to be highly detailed for previous simulations resulted in unexpected points of interference on the winding forms. In other cases, although the simulation indicated reasonable reach and access, over-extended tool bits resulted in excessive chatter. Whenever unanticipated issues such as this were encountered, the result was that advanced CNC programming steps often had to be heavily modified or even re-written. In the first weeks of machining, considerable effort was expended in identifying which types of cutting tools would permit efficient cutting of the new Stellalloy. In general, Stellalloy machines well, but its high strength requires high tool pressures, which aggravated machining with extended cutting tools. Fortunately, an early imagined concern about possible wide variations of the machining characteristics in a casting has proven to be unfounded. The basic steps in the machining process are:

1. The casting is carefully positioned on a rigid angle fixture, checking to assure that the machined surfaces all have adequate stock.
2. “Roughing” operations are performed on the flanges and mounting pedestals.
3. With the casting mounted in a vertical position, 3-axis CNC machining is performed on the winding surfaces and the poloidal electrical break is rough cut. (Fig. 8). In future castings, the cutting of the poloidal break will be left to a final operation in order to better maintain the rigidity of the part. The winding form is machined to within 0.75 mm of its final dimension.

Figure 8. A Casting During 3-Axis CNC Machining

4. Final machining operations are performed on a 5 axis CNC machine.
5. The winding surfaces are ground and polished to a finish <125 μin. and the poloidal electrical break is assembled.
6. Final inspections are performed: visual inspection of machined surfaces; magnetic permeability tests; liquid penetrant inspection; electrical testing of the poloidal break, and dimensional inspection with a large gantry CMM (Fig. 9).

Figure 9. CMM Measurement of the C1 Winding Form

The C1 casting is shown in the photo in Fig. 10 prior to the assembly of the poloidal elecrical break.

Figure 10. Photo of the C1 Winding Form

V. SUMMARKY

During this first year of production, an incredible amount of progress has been made. Most importantly, the required technical and quality requirements are being met. The team has worked through a number of “start-up” challenges ranging from volatile metals market conditions to machining of a part with extremely complex geometry with a new alloy. Although the first parts have taken longer than anticipated, the “lessons learned” are for the most part applicable to all three types. All of the patterns have been fabricated; seven of 18 castings have been produced; all machining fixtures have been fabricated, “reach and access” and cutting tool issues have been resolved; one casting has been completely machined and a second is about 80% complete. There has been considerable improvement in schedules at both the foundry and machine shop which give confidence that the winding forms will be produced on a schedule consistent with NCSX’s first plasma date of July, 2009.

VI. ACKNOWLEDGMENT

Our thanks to the NCSX Project and EIO Production Teams whose dedicated efforts and talents made these accomplishments possible. Our thanks also to Richard Reed of Cryogenic Materials, Inc., Robert Keilbach of the

Washington Group, and Robert Walsh of the National High Field Magnet Laboratory for their expert advice on technical issues. This work is supported by USDOE Contract DE-AC02-76CHO3073.

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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
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