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Component Manufacturing Development for the National Compact Stellarator Experiment (NCSX)

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Abstract. NCSX is the first of a new class of stellarators called compact stellarators which hold the promise of retaining the steady state feature of the stellarator but at a much lower aspect ratio and using a quasi-axisymmetric magnetic field to obtain tokamak-like performance. Although much of NCSX is conventional in design and construction, the vacuum vessel and modular coils provide significant engineering challenges due to their complex shapes, need for high dimensional accuracy, and the need for high current density in the modular coils due space constraints. Consequently, a three-phase development program has been undertaken. In the first phase, laboratory / industrial studies were performed during the development of the conceptual design to permit advances in manufacturing technology to be incorporated into NCSX's plans. In the second phase, full-scale prototype modular coil winding forms, compacted cable conductors, and 20-degree sectors of the vacuum vessel were fabricated in industry. In parallel, the NCSX project team undertook R&D studies that focused on the windings. The third (production) phase began in September 2004. First plasma is scheduled for January 2008.

1. Introduction

Stellarators are attractive because they can provide the solution to steady state operation, which is one of the most critical problems for magnetic fusion energy. Stellarators are capable of steady state operation without current drive and without feedback control or rotational drive. This is accomplished by producing the closed magnetic surfaces needed to confine the plasma with a set of non-planar coils. Compact stellarators hold the promise of retaining the steady state feature of the conventional stellarator but at a much lower aspect

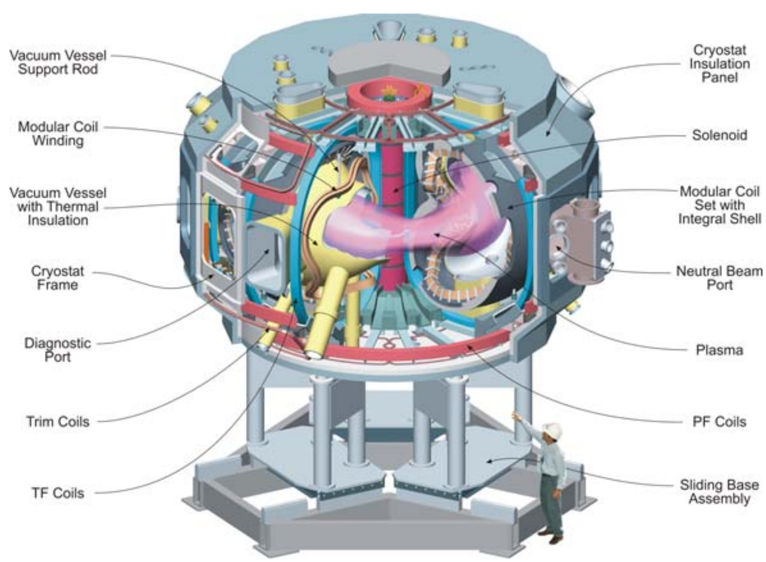


Figure 1. Details of the National Compact Stellarator Experiment

ratio (R/⟨a⟩ =4.4 for NCSX) than those of previous optimized stellarator designs (typically up to 10). In spite of its 3D shape, the NCSX has a quasi-axisymmetric magnetic field, which is expected to give it confinement properties similar to those of tokamaks. The plasma in a compact stellarator has a complex shape that is confined in a highly shaped vacuum vessel surrounded by close-fitting, complex, precisely shaped windings that are required to operate at high current density. The NCSX device is shown in Figure 1. Most of NCSX, including the PF, TF, and Trim Coils, are conventional in design and construction. However, two of NCSX's key components, the vacuum vessel, shown in Figure 2, and the modular coils, shown in Figure 3, are highly unusual and challenging from the point of view of engineering and manufacturing due to their complex shapes, need for precise dimensional control, and need for high current density in the windings. Consequently, the three-phase manufacturing development program outlined in the Abstract was devised to develop these key components.

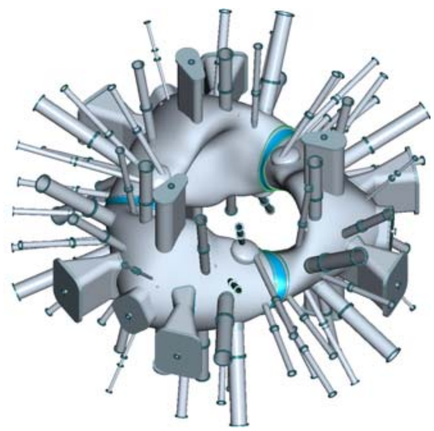


Figure 2. The NCSX Vacuum Vessel Assembly

Figure 3. One of the three modular coil winding form types.

2. NCSX Modular Coils and Vacuum Vessel Design Development

Manufacturing feedback was necessary throughout the design development process from both industry and laboratory R&D activities to assure that the designs would not only meet their functional requirements, but that the manufacturing processes they required were within the state of the art and that the designs would meet the project's cost and schedule objectives.

Modular Coil Development: For the modular coils, the process began with studies of non-optimized conceptual designs to develop engineering constraints such as the conductor bend radii, coil to coil spacing, and coil to plasma spacing, coil twisting, current density, and neutral beam access requirements. An optimized modular coil design was then developed through an iterative physics / engineering optimization process using a specifically developed suite of computer codes [1], which optimized the coil geometry to achieve targeted plasma physics properties, while satisfying engineering constraints. The resulting modular coil set, consisting of six each of three coil types, is shown in Figure 4.

Next, the engineering details of the coil winding and its structure were developed. A basic requirement set by the necessity for magnetic islands to be <10% of the total flux was that the modular coils be located within +/- 1.5 mm. This tolerance was divided equally between the winding form, the winding, and assembly. After considering many configurations, the configuration shown in Figure 5 was chosen. It consists of cast and machined stainless steel winding form shells with integral "T" shaped feature upon which flexible stranded copper conductors are wound. The shells are joined at final assembly via bolts at the insulated flanges to form a rigid, toroidally continuous structure. This is a good structural configuration since the electromagnetic loads are predominantly radially outwards and laterally attractive between the winding packs. It is also a good configuration from the manufacturing point of view since it provides good access for machining and winding [2] [3]. Each winding form has one poloidal electrical break to achieve a time constant < 20 ms. Details of the coil are shown in Figure 6.

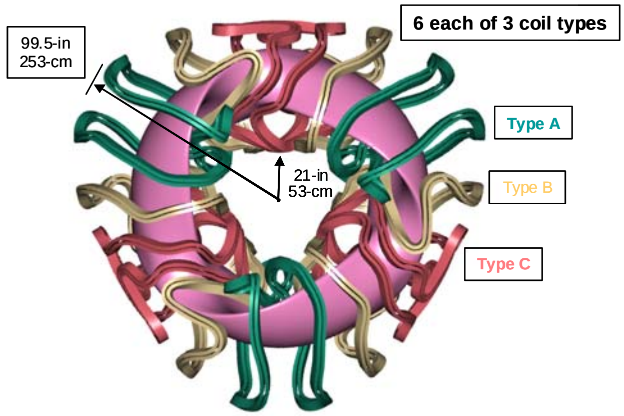


Figure 4. The NCSX Plasma and Modular Coils.

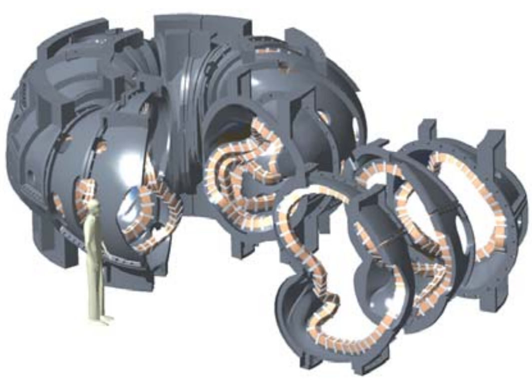


Figure 5. NCSX Modular Coil Structure

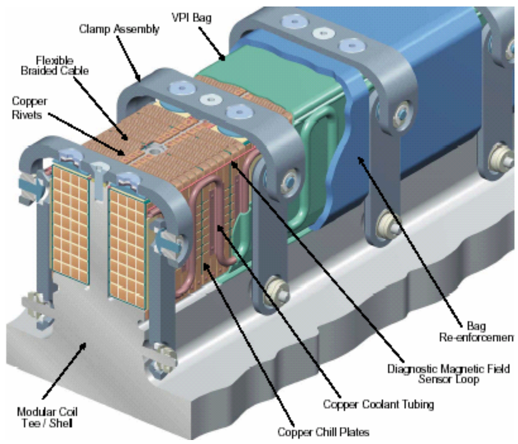


Figure 6. NCSX Modular Coil Details

Vacuum Vessel: After the modular coils were defined, a number of operating scenarios were examined to set the operating boundaries of the plasma. The size and shape limitations for the vacuum vessel (including its thermal insulation and in-vessel components) were thus bounded by plasma boundaries on the inboard side and the modular coil surfaces on the outboard side. The final shape of the vessel was developed through an iterative process that considered both the desire to maximize the vessel interior space for experimental hardware and the need to have adequate allowances for manufacturing tolerances and assembly. The vessel is built in three segments corresponding to the three field periods to permit the modular coils to be positioned over it during assembly.

3. The Phase I (Initial) Manufacturing Studies

Limited industrial manufacturing studies of approximately 3 months duration were undertaken in the fall of 2001 for the vacuum vessel and modular coils while NCSX's conceptual design was being developed. Early involvement was sought so that study findings could be used to guide the development of the design. Design recommendations, potential manufacturing methods, budgetary manufacturing costs and schedules, and a review of the proposed manufacturing specifications were requested from the study participants. Five contractors participated in the modular coil studies – two studied the modular coil assemblies (i.e., the cast stainless steel winding forms and the windings), two studied just the winding form castings, and one studied just the windings. Five other contractors participated in the vacuum vessel studies. The studies for both the vacuum vessel and modular coils were very productive and well met their goals. For the modular coils, the studies highlighted a number of critical areas that required additional work: the coil cooling method; the behavior of the stranded copper conductor and control of tolerances; the need for repeatable, high quality vacuum / pressure epoxy impregnation, and the need for well thought out inspection requirements. One result of these studies was a project decision to have the modular coil winding R&D and manufacture performed by the project staff in order to provide the rapid R&D feedback necessary to permit concurrent engineering of the modular coils and development of the integrated design of the device. This decision was supported by the availability of coil expertise at PPPL from its many years of in-house coil manufacture and the availability of adequate space for coil winding at the former TFTR Test Cell. It was decided that the modular coil winding forms would be procured from industry. For the vacuum vessel, the most significant finding was that not only was the vessel within the state of the art of industry, but there were a number of viable fabrication methods, including explosive forming, hot forming, cold forming, and possibly casting.

4. The Phase II (Prototype) Manufacturing Studies

Following the Phase I studies, three parallel studies were undertaken. Manufacturing R&D and prototype studies associated with the modular coils were undertaken at PPPL while industrial prototype / manufacturing studies were undertaken on the vacuum vessel and on the modular coil winding forms.

a. Modular Coil R&D Studies

A series of increasingly complex coil winding studies, illustrated in Figure 7, were performed at PPPL to provide the information necessary to finalize the designs of the modular coils and to develop the coil manufacturing methods. One of the most significant studies, shown in the second photo pane, resulted in the successful development of the bag mold vacuum / pressure impregnation (VPI) processing method. The challenge was to develop a reliable sealed enclosure around the highly shaped modular coil windings suitable for this critical process. The rather broad and complex shaped integral shell structure precluded the standard bag molding method. The bagging method ultimately developed utilizes a self-vulcanizing silicon rubber “bag” restrained in a groove at the base of the “T” by a copper tube. A hard shell of epoxy / glass felt is formed over the bag to reinforce it. The entire VPI procedure is performed in an autoclave, with the autoclave pressures adjusted throughout the process to minimize pressure differentials across the bag boundary. Reliable epoxy impregnation of the cable strands, verified by scanning electron microscope examination, was achieved with this process. Tests were performed on the impregnated cable at 77^0K to determine the strength, transverse and axial moduli, and thermal characteristics. A racetrack shaped winding was tested to qualify the fatigue properties of the cable for twenty times life at full operating load.

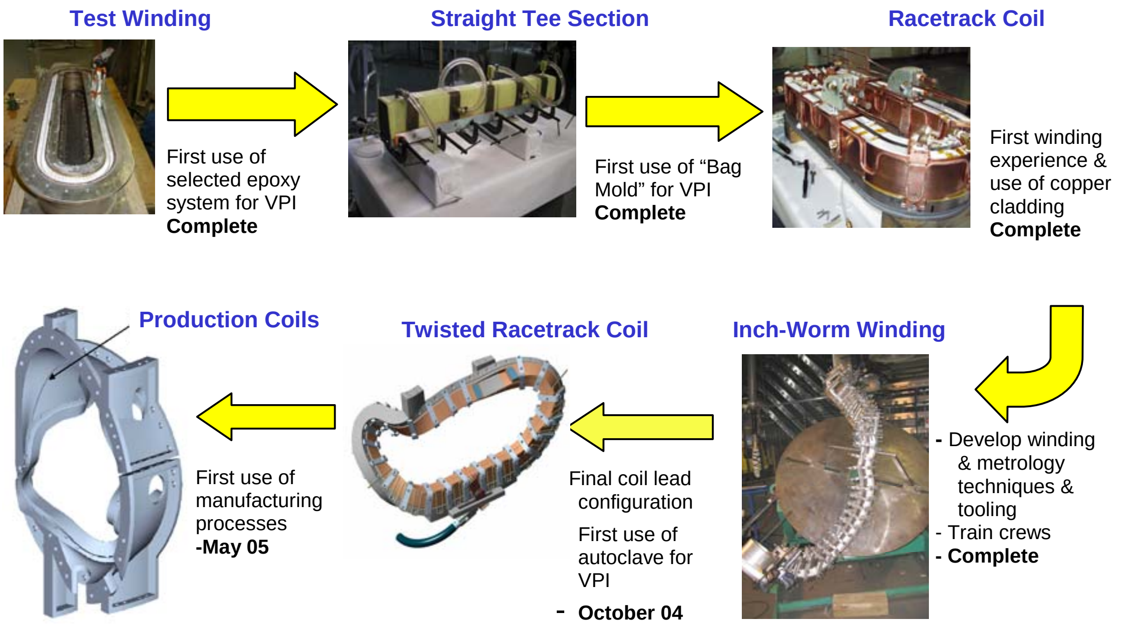


Figure 7. NCSX Modular Coil Winding Manufacturing R&D Studies

b. Industrial Prototype Manufacturing / Studies: This phase commenced with the award of two contracts each for a full-scale modular coil Type C winding form and for a full scale 20 degree vessel segment with a single port in March of 2003. The primary elements of the scope of work included development of the detailed manufacturing and quality assurance plans and procedures; the development of budgetary cost and schedule data for use in NCSX's project planning; the prototype manufacture, and as a last deliverable, a fixed price and schedule proposal for the manufacture of the production parts.

c. Vacuum Vessel Prototype: The vessel is manufactured by welding together press-formed panels made of Inconel 625. The geometry of the prototype was measured using a multi-link component-measuring machine. A so-called "point cloud" 3-D representation of all the measurements is shown in the left image in Figure 8. This was overlaid on the CAD model shown on the right to determine the deviations from ideal. The prototype was able to achieve the specified +/- 4.7 mm tolerance.

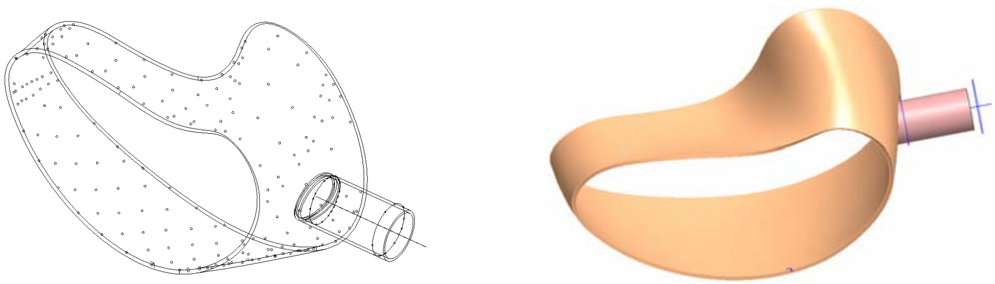
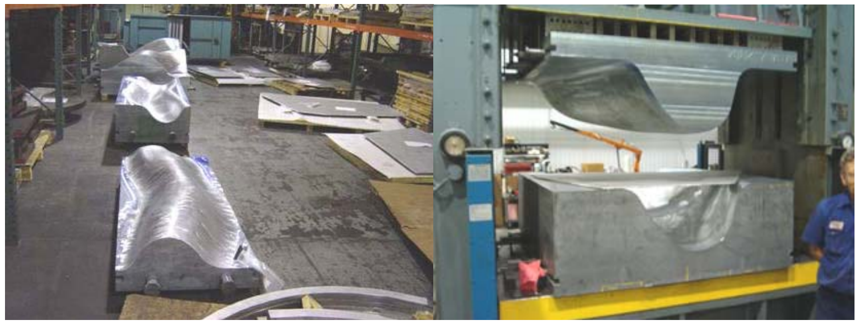


Figure 8. Comparison of the CMM Measurements to the CAD Model

The photos shown in Figure 9 is an overview of the prototype vacuum vessel manufacturing process used by Major Tool and Machine, Inc., who is the manufacturer of the production vacuum vessel.

Left photo: a die set.
Right photo: press forming of a panel.



Left photo: assembly fixture
Right photo: the welded vessel body

Left photo: vessel port weld detail.
Right photo: completed prototype.

Figure 9. Fabrication of the NCSX Prototype Vacuum Vessel Segment

d. Winding Form Prototype: The winding forms are sand cast of an alloy specifically developed by MetalTek, Inc. It was developed to assure that a permeability of < 1.01 can be achieved. It is a variant of CF8M stainless steel named Stellaloy 2 (CF8MnMN Mod). The minimum mechanical properties are given in Table 1. This alloy requires only air quenching to develop these properties, and thus avoids distortion concerns associated with water quenching.

Temperature	**77K**	**293K**
Elastic Modulus	21 Msi (144.8 Gpa)	20 Msi (137.9 Gpa)
0.2% Yield Strength	72 ksi (496.4 Mpa)	34 ksi (234.4 Mpa)
Tensile Strength	95 ksi (655 Mpa)	78 ksi (537.8 Mpa)
Elongation	32%	36%
Charpy V – notch Energy	45 ft. lbs. (61.0 J)	60 ft-lbs (81.3 J)

TABLE 1. MINIMUM PROPERTIES OF THE NCSX WINDING FORM ALLOY.

The steps required to produce a machined casting are outlined Figure 10. The patterns used to produce the mold were contour milled using a CAD model dimensionally adjusted from the NCSX provided CAD model to compensate for thermal contraction of the casting and to provide additional metal ('padding') to allow for uncertainties to assure the final casting can be machined from the resulting part. A prototype winding form casting is shown in Figure 11.

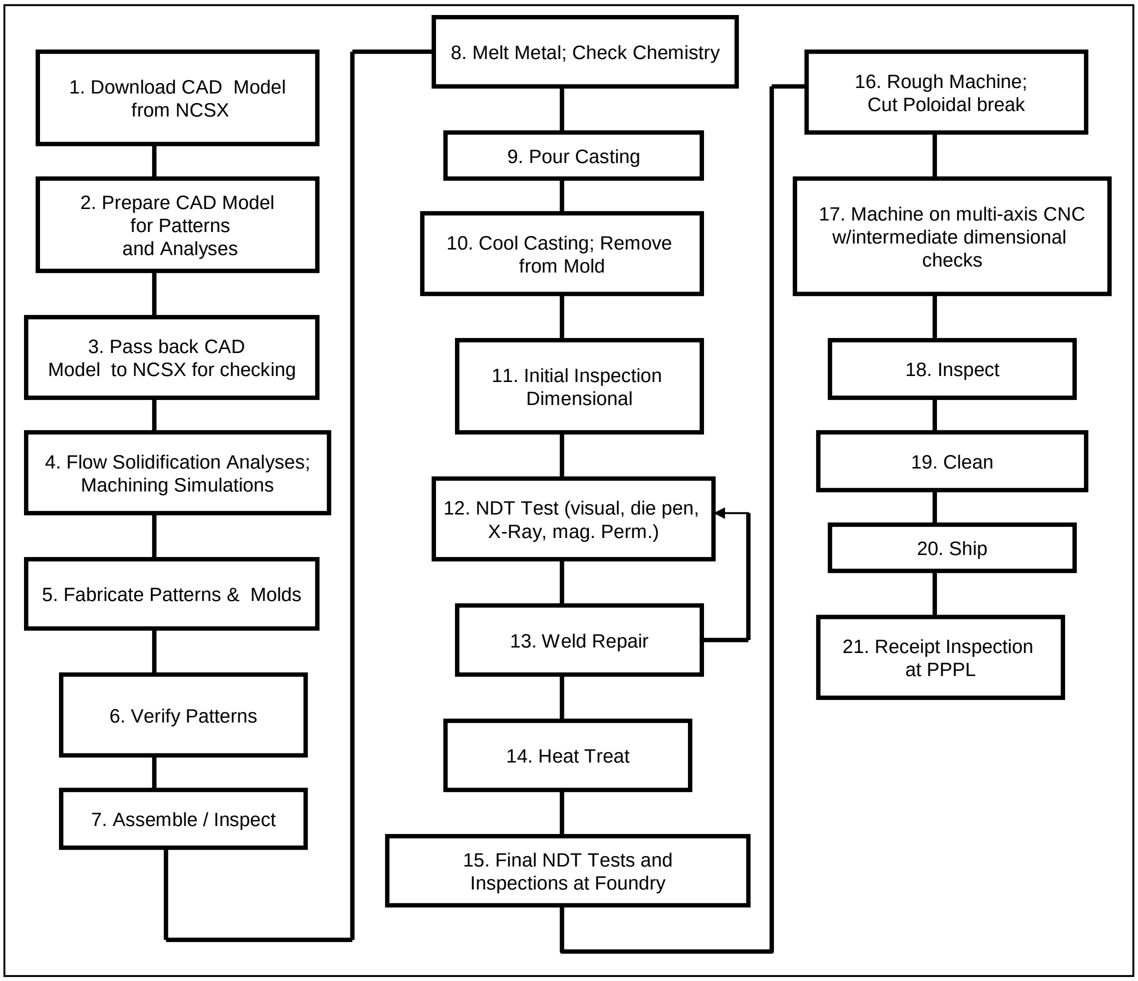


Figure 10. NCSX Modular Coil Winding Form Manufacturing Process

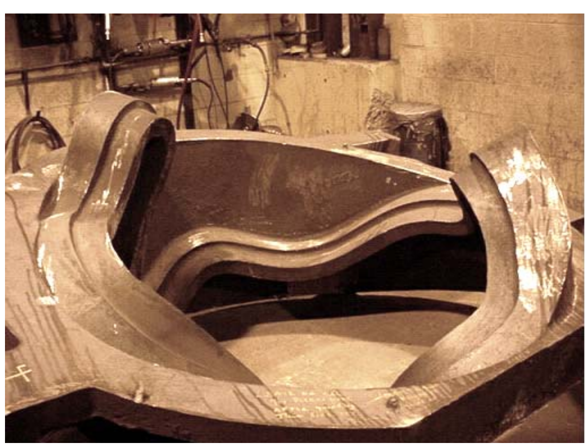


Figure 11. A Prototype Winding Form

5. The Phase III (Production) Phase

The final deliverable from the Phase II Prototyping industrial subcontracts was a fixed cost and schedule proposal for the production vessel or winding forms. Based on evaluations of these proposals, a $8 M subcontract was issued to a team led by Energy Industries of Ohio, Inc. of Independence, Ohio for the manufacture of the (18) winding forms. Team members include the C.A. Lawton Company, Pattern Division, of DePerre, Wis. MetalTek International, Carondelet Division, of Pevely, Mo.; and Major Tool and Machine, Inc., of Indianapolis, Ind. The first winding form is scheduled for delivery in May, 2005, and the final (18^{th}) winding form is scheduled for delivery by August of 2006. A subcontract for $4.5 M was awarded to Major Tool and Machine, Inc. for the vacuum vessel. It is to be delivered in the fall of 2005.

References

[1] G. H. Neilson, et al. Physics Considerations in the Design of NCSX, 2002 Fusion Energy Conference, Lyon; paper IAEA-CN-94/IC-1.

[2] B. E. Nelson, et al. Engineering Aspects of Compact Stellarators, 2002 Fusion Energy Conference, Lyon; paper IAEA-CN-94/FT/2-4.

[3] D. Williamson, et al., Modular Coil Design Developments for the National Compact Stellarator Experiment (NCSX), Proc. 23rd Symposium on Fusion Technology (SOFT), Venice, 2004, to appear.

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Atlas Foundry and Machine, Tacoma, WA.;
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International Association “INTERM”, Kyiv, Ukraine.

Phase II:

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Rohwedder, Inc., Orlando, FL. and team member Precision Metal Works, Ltd.
Energy Industries of Ohio (EIO); Independence, OH. and team members Atlantic Technical Components; buyCASTINGS, Inc.; MetalTek International; Magna Machine Co.; CA Lawton Co.; Deformation Control Technology Inc.; Finite Solutions Inc.; Altair Engineering Inc..
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