COMPONENT MANUFACTURING DEVELOPMENT for the NATIONAL COMPACT STELLARATOR EXPERIMENT (NCSX)

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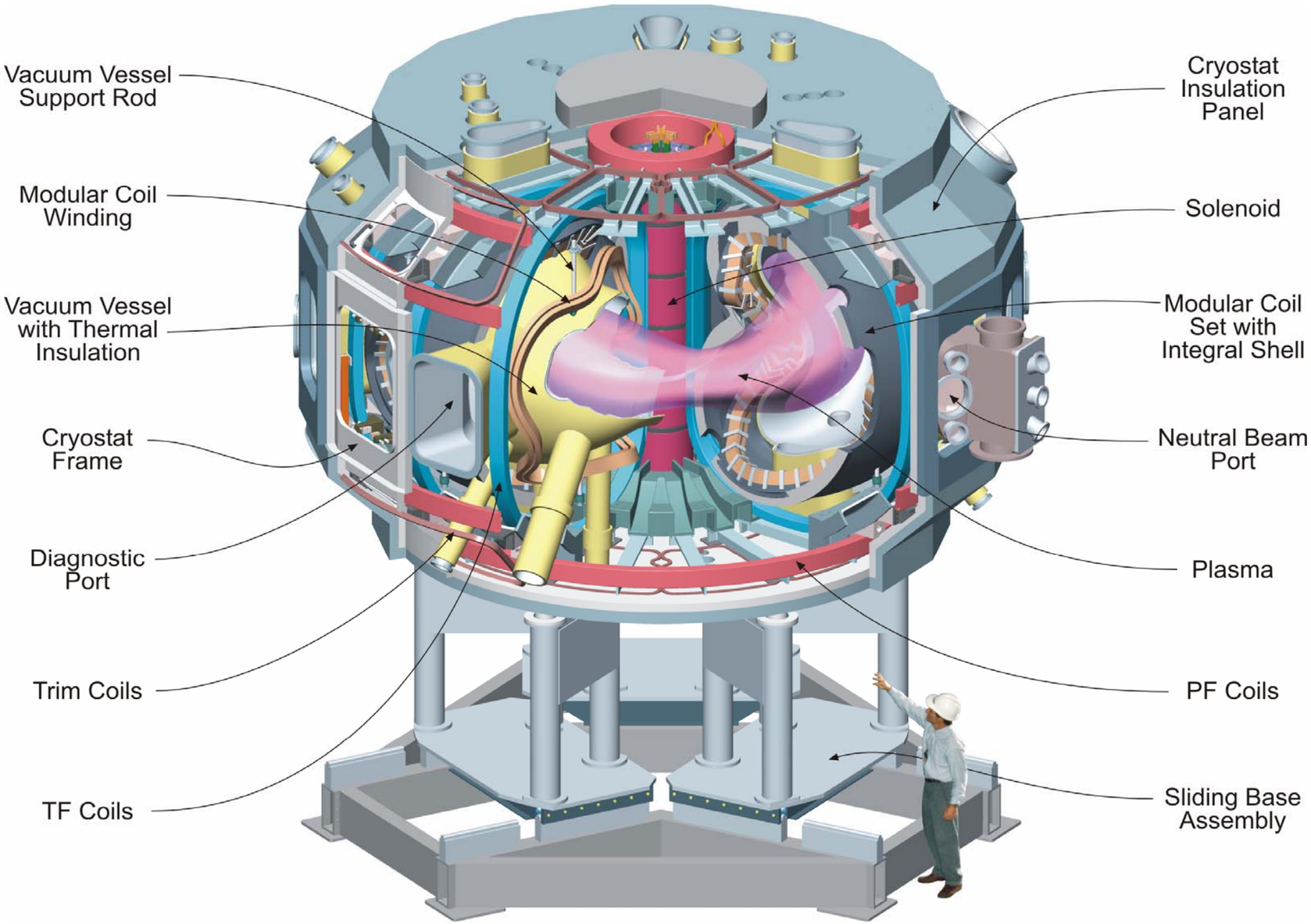
Abstract

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 high current density required in the modular coils due to 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 which focused on the windings. The third (production) phase began in September 2004

NCSX



- **First Plasma January, 2008.**
- **Major radius = 1.4 m.**
- **B =2.0 T (0.2 s pulse).**
- **All coils (Toroidal Field (TF), Poloidal Field (PF), Modular Coils, and Trim Coils) are cryoresistive.**

The Three Phases of NCSX's Manufacturing Development Effort

<u>Phase I.</u> Limited manufacturing Studies (Fall of 2001; duration ~ 3 mos.)

- Provided input on the design, potential manufacturing methods, cost & schedule.

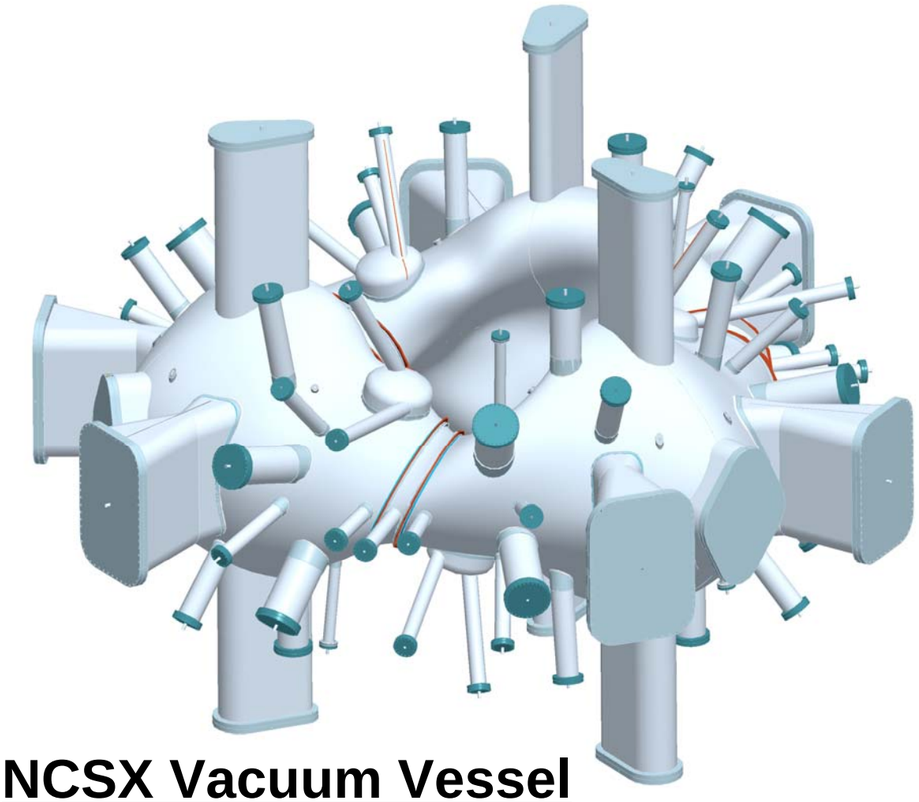
<u>Phase II.</u> Detailed Manufacturing Studies & Prototypes
(March, 2001 - August, 2004)

- 2 teams for the vacuum vessel; 2 teams for the winding forms. Tasks included:
  - Detailed manufacturing & quality assurance plans.
  - Budgetary cost and schedule estimates for project planning.
  - Prototypes
  - As a last deliverable, fixed price and schedule proposals for the production parts.

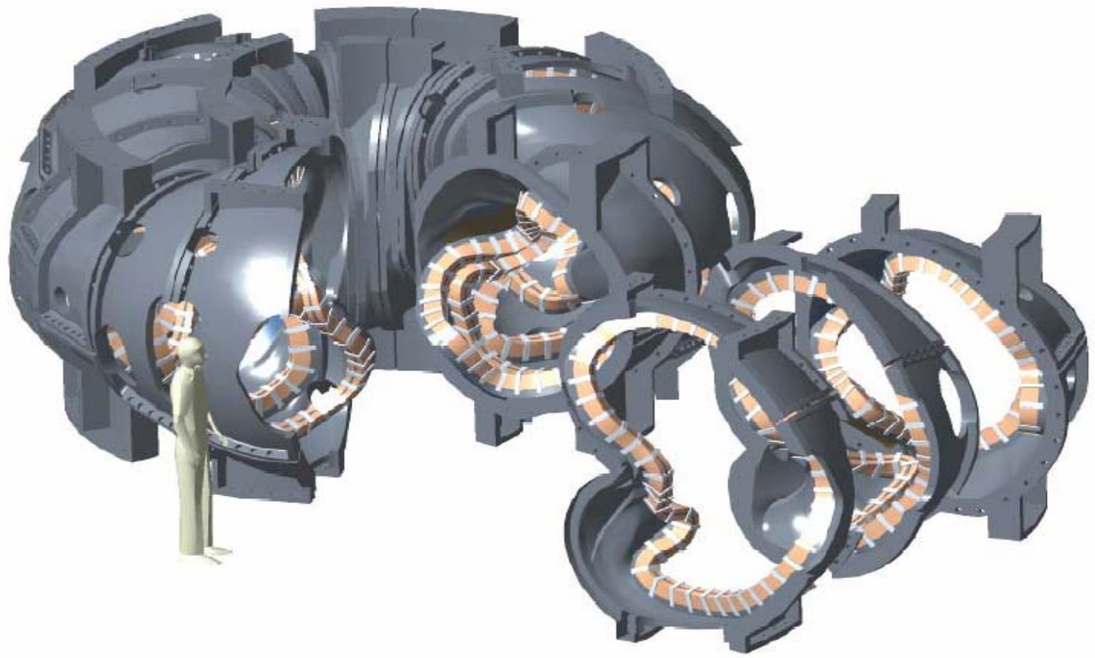
<u>Phase III.</u> Production. This phase began September'04.

- One fixed price and schedule subcontract awarded for the vacuum vessel; one fixed price and schedule subcontract for the modular coil winding forms.

A Focused Manufacturing Development Program Addressed Challenges



NCSX Vacuum Vessel



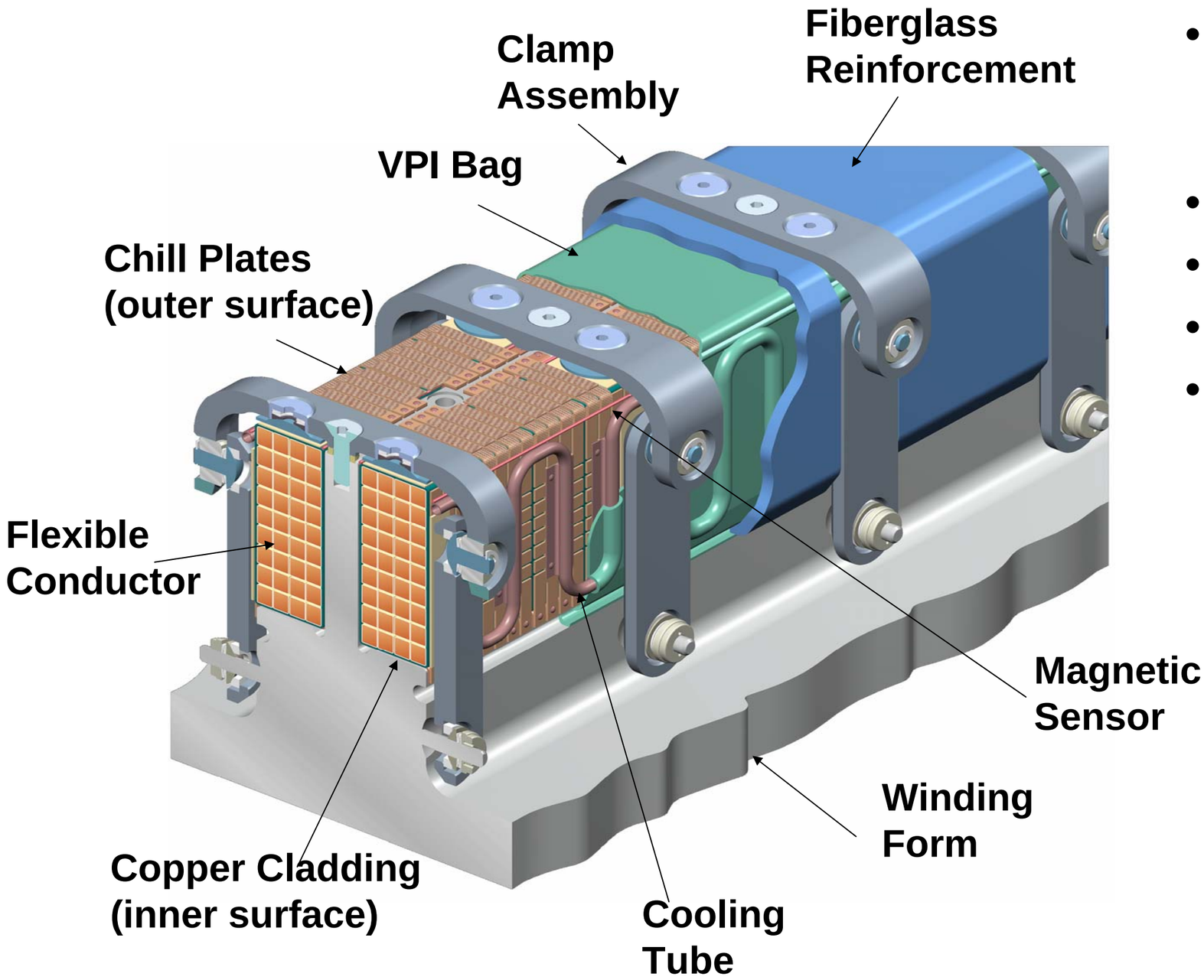
NCSX Modular Coils

These components were recognized as unusual and challenging from the manufacturing point of view from their conception.

Key Questions :

How can these parts be made?
Can these tolerances be achieved?
What will the costs and schedules be?

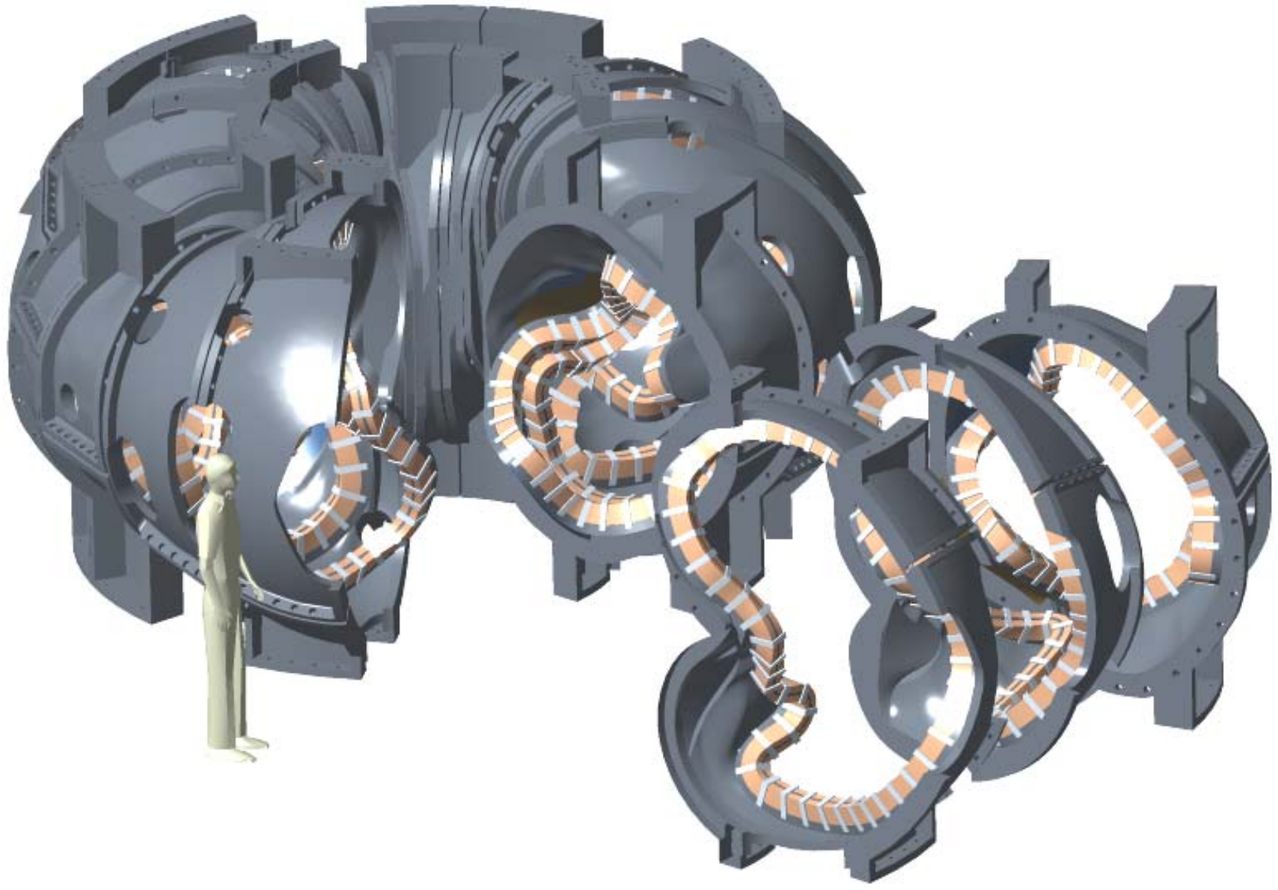
Modular Coil Details

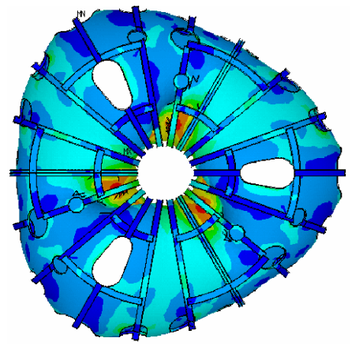


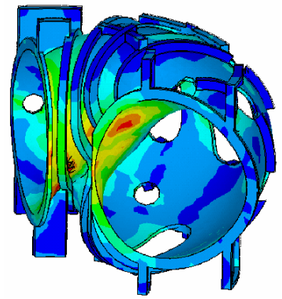
- Coils are wound on SS winding form and vacuum/ pressure impregnated in place.
- epoxy 20 or 18 turns / coil
- 23 kA / turn
- J=13.0 kA / cm^2
- $T_{Operating} = 85 – 125^0K$

Flexible Conductor (4 in hand per turn)

Modular Coil Structure

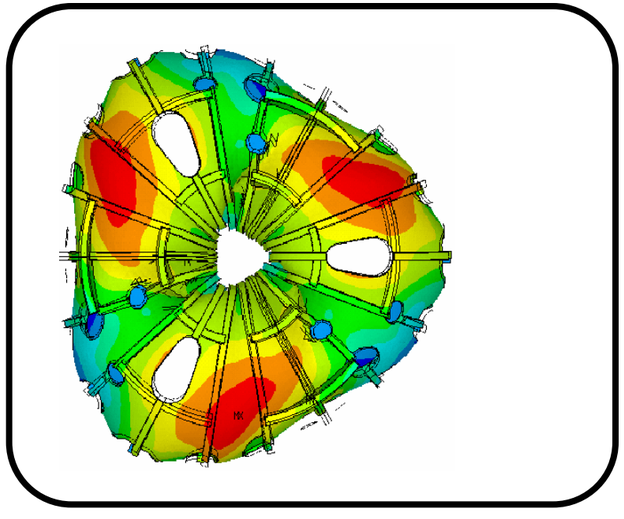






Von Mises stress distribution

Max. Seqv = 87.4 MPa (13 ksi), F.S. ~4

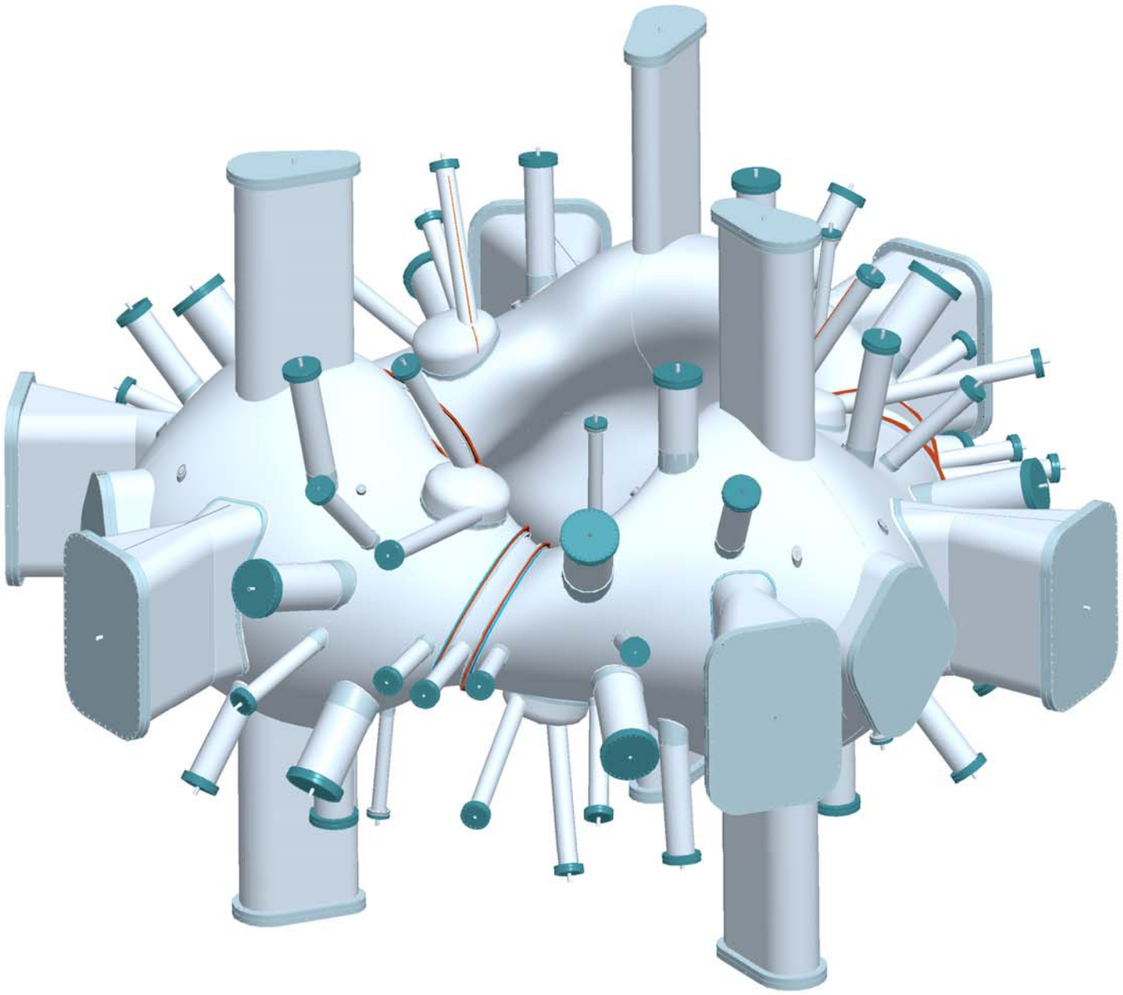


Total displacement contours

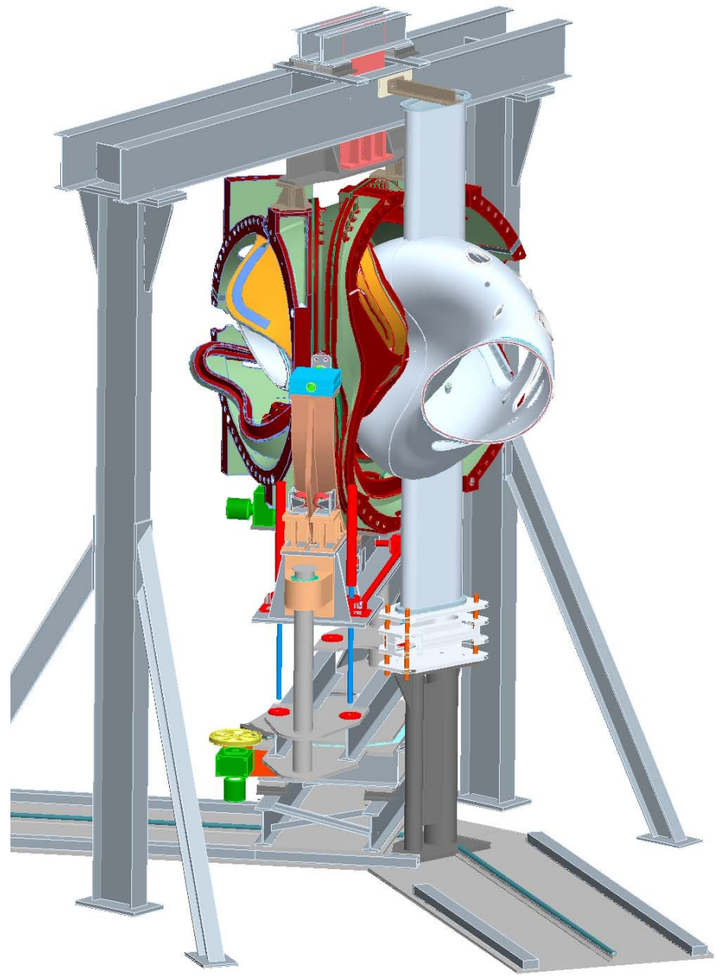
Max displacement ~ 0.5 mm

- **Structure consists of individual modular coil forms that are bolted together.**
- **Supports all coils; is the primary structure of NCSX**
- **1 poloidal electrical break/coil; 1 toroidal electrical break per period.**
- **Tolerances: Machined surfaces: + / - 0.5 mm.; shell profile tolerance: +6mm / -0 mm.**

Vacuum Vessel Design



NCSX Vacuum Vessel Shown with Ports Installed



Vacuum Vessel / Modular Coil Assembly

Ports are installed after the modular coils are in place.

- **Vessel shape chosen to maximize the vessel interior space & provide adequate assembly clearances.**
- **Built in three periods to permit assembling with the modular coils.**
- **Shell position tolerance: +/- 4.8 mm.**
- **Inconel 625, 0.95 mm thick. Total weight: 11.5 tonnes. Major Diameter: 4.4m.**
- **Vessel Bakeout T= 350^0 C; First Wall Bakeout T=350^0C; Operating T=40^0C.**

Details & Accomplishments of the Phase I (Limited Manufacturing) Study in 2002

Significant Winding Form Study Findings: Identified a number of areas that require additional work such as coil cooling, achievement of tolerances, inspection requirements.

- As a result, it was decided to procure the winding form from industry but perform additional R&D on the modular coils and wind the "production" coils at PPPL to permit concurrent engineering.

Significant Vacuum Vessel Study Findings: The vessel is within the state of the art of industry, and can be potentially manufactured in a number of ways, including hot forming, cold forming, explosion forming, and investment casting.

Participants:

Osterby Gjuteri, AB; Osterbybruk, Sweden;
Mitsubishi Electric Power Products, Inc. Warrendale, PA.;
Hitachi, Ltd., Tokyo, Japan;
Ansaldo Superconduttori s.p.a., Genova, Italy;
Atlas Foundry and Machine, Tacoma, WA.;
PCC Structurals, Portland, OR.
International Association "INTERM", Kyiv, Ukraine.

The Phase II Industrial Manufacturing Studies

March 2003-August 2004

Winding Form Participants:

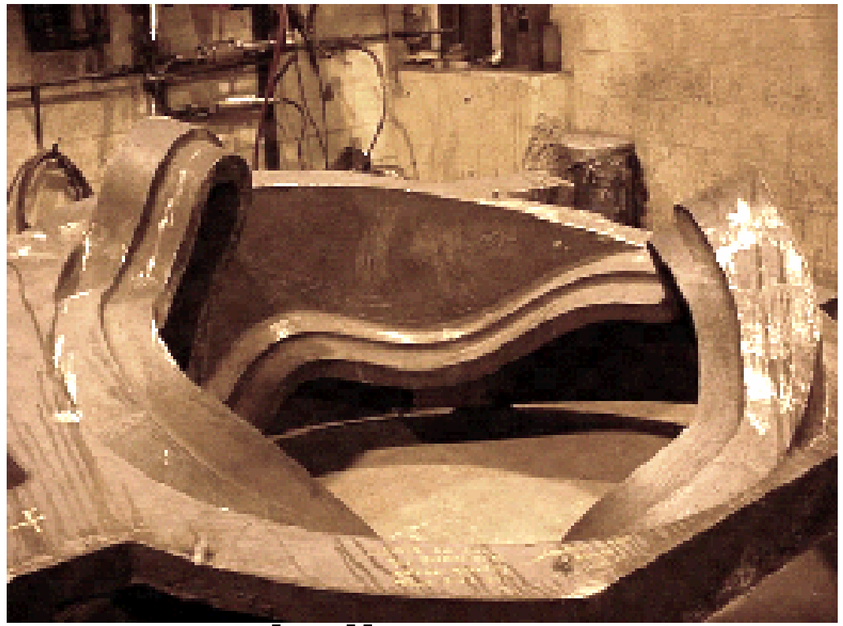
- The team of J.P. Pattern, of Butler, Wis[1].
- The team of Energy Industries of Ohio, Independence, OH.[2]

VV Participants:

- Major Tool and Machine, Inc. of Indianapolis, IN
- Rohwedder, Inc. of Orlando, Fla. and Precision Metal Works.

Work Scope :

- Detailed manufacturing and quality assurance plans.
- Cost and schedule information for use in developing project plans.
- **Prototypes**
- Fixed price and schedule proposals for the production parts.



EIO Team Winding Form Prototype

Major Tool and Machine, Inc. Vacuum Vessel Prototype

[1]TK Technical Innovations; Waukesha –Kramer International; Remmele Engineering.

[2] BuyCastings.Com; MetalTek International.; Magna Machines; Altair, Inc.; Deformation Controls; C.A. Lawton; Atlantic Technical Components, Inc.

Flexible Conductor Specification Developed Based on Manufacturing Trials at New England Wire & Cable and Tests at PPPL

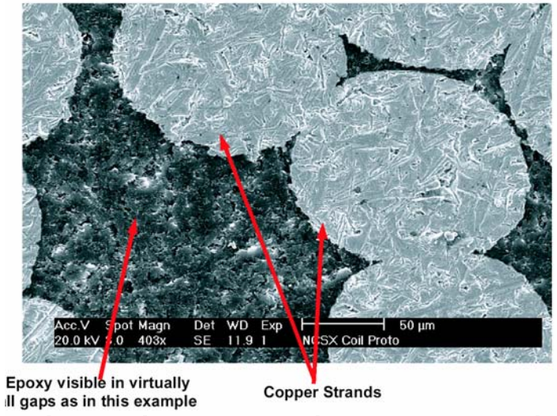
Conductor Specifications:

- OFHC copper- 34 AWG bare copper (0.0063 in. diameter) per ASTM B-577
- 3240 strands
- Conductor will be manufactured with no lubricants (clean)
- Conductors will fabricated using copper rope that was compacted to required dimensions (tolerance +/- 0.2 mm)
- Conductor will have 0.1 mm thick Nylon serve that assists with forming the conductor and helps to minimize loose strands

Turn Insulation:

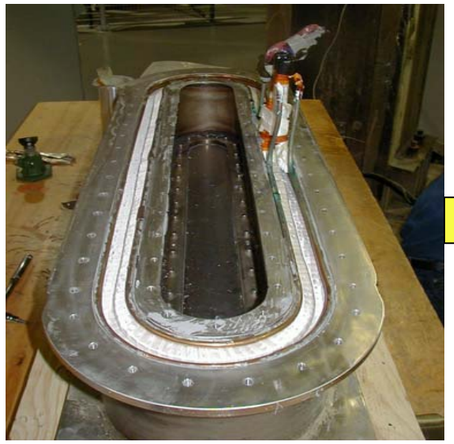
- Conductor will be insulated with (1) half-lapped layer of nominal 0.1 mm thick S-2 fiberglass tape

Flexible Conductor for NCSX

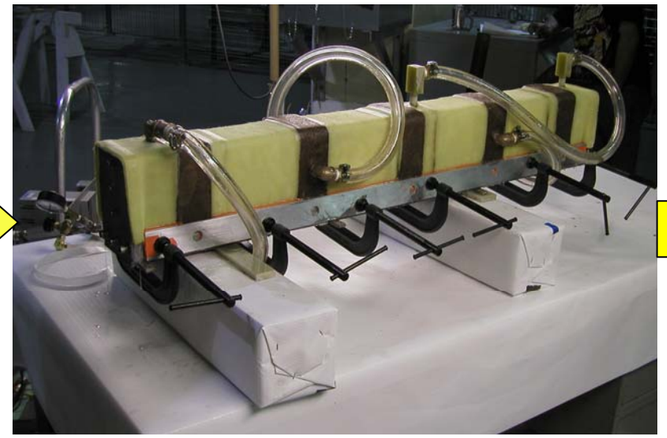


Scanning Electron Microscope Photo Showing Epoxy Impregnation Results

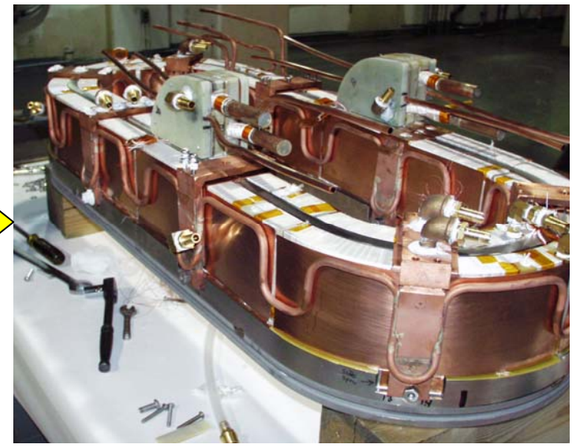
NCSX Modular Coil Winding Development



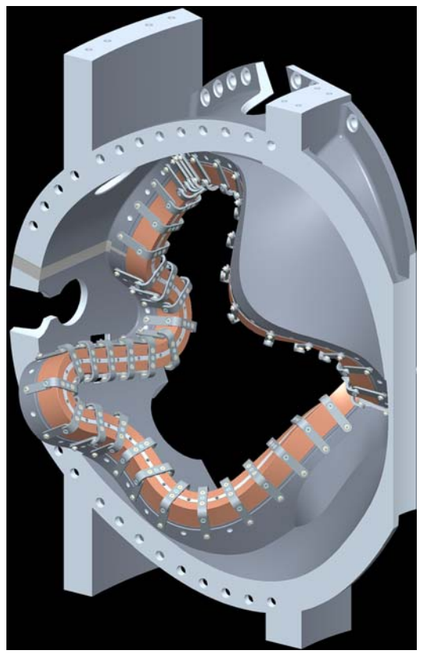
Univ. of Tennessee Coil - First use of selected epoxy system for VPI. **Complete.**



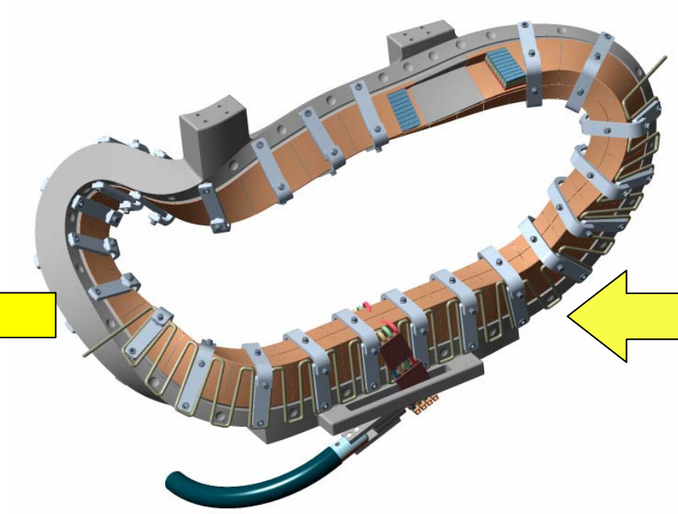
Straight "T" Coil - First use of "Bag Mold" for VPI. **Complete.**



Racetrack Coil - First winding experience & use of copper cladding. Complete.



Production Coils – Integrated coil manufacture. **May 05**



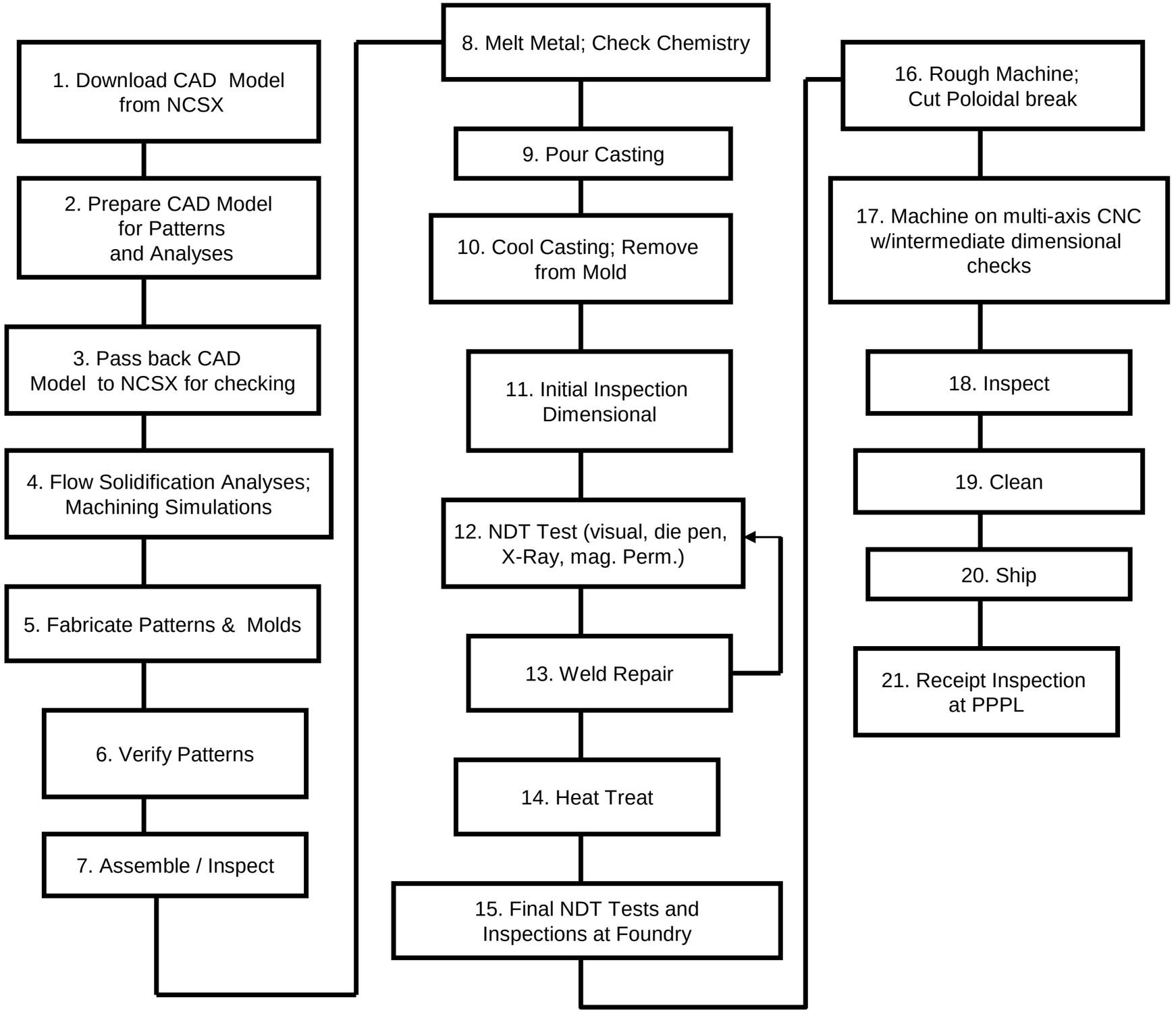
Twisted Racetrack Coil -

Final coil lead configuration

- First use of autoclave for VPI
- **October 04-April 05**

"Inchworm Winding" - Develop winding & metrology techniques & tooling

- Train crews
- **Complete**



Manufacturing Flowchart for the Modular Coil Winding Forms

A Custom Low Magnetic Permeability Stainless Steel Alloy Was Developed for the Winding Forms

- It is a variant of CF8M stainless steel named Stellaloy 2 (CF8MnMN Mod) by MetalTek International, its developer.
- Avoids the necessity of water quenching and concerns about distortion.

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)

Minimum Properties for the NCSX Modular Coil Winding Form Stainless Steel Alloy.

Phase II Accomplishments:

Detailed Manufacturing / Inspection / Test and Quality Assurance Plans Were Developed and Demonstrated

A Die Set

Press-Forming a Panel

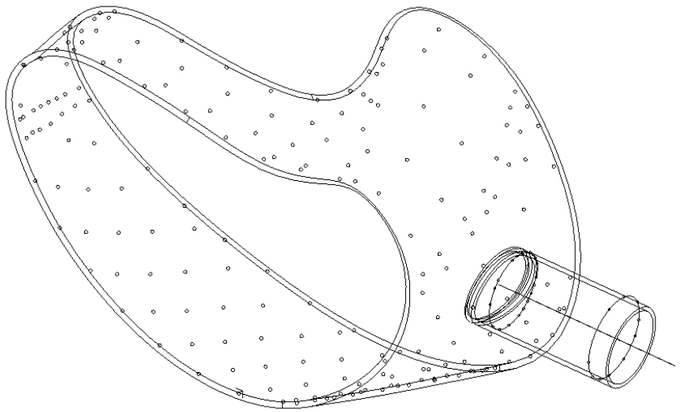
Vessel Prototype

Weld Fixture

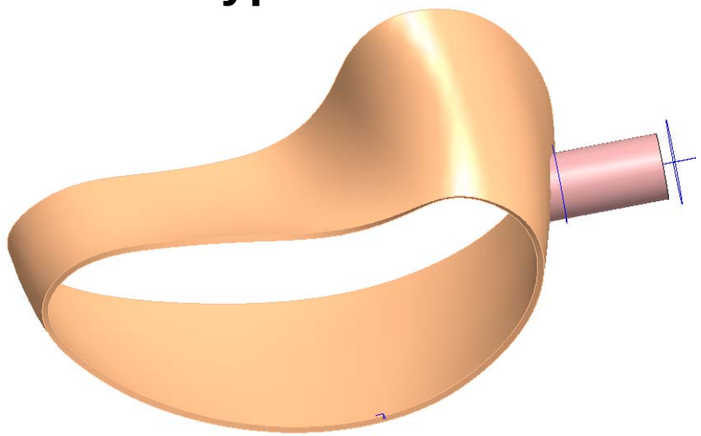
Welded Prototype Segment

Photos Courtesy Major Tool and Machine, Inc.

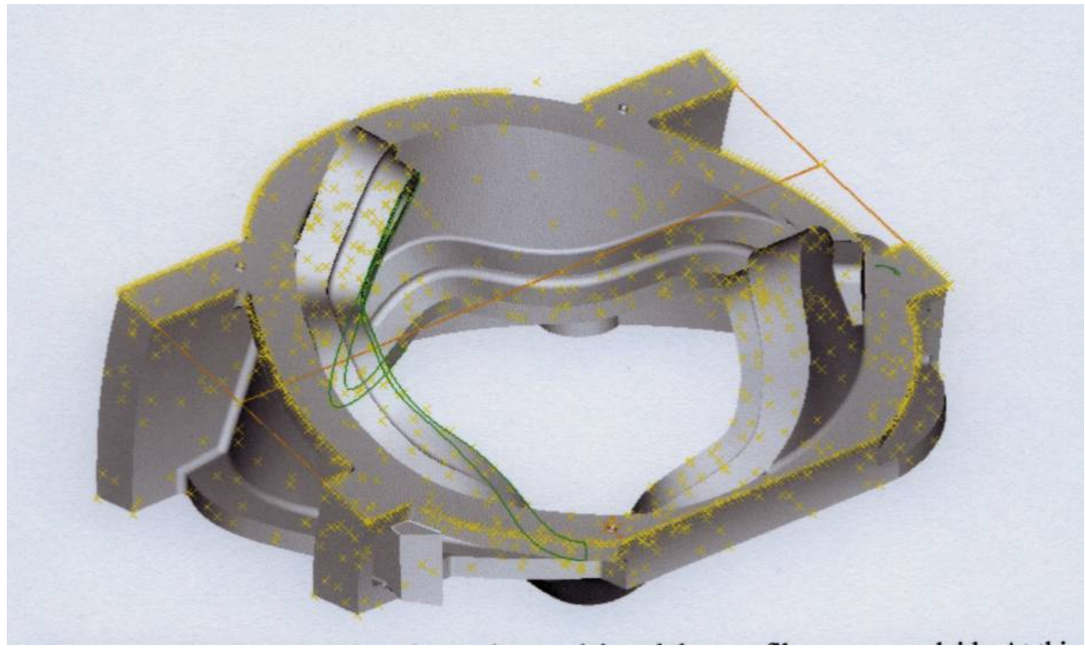
Prototypes Achieved Dimensional Goals



“Point Cloud” 3D Representation of VV Prototype Measurements



CAD Model of VV Prototype

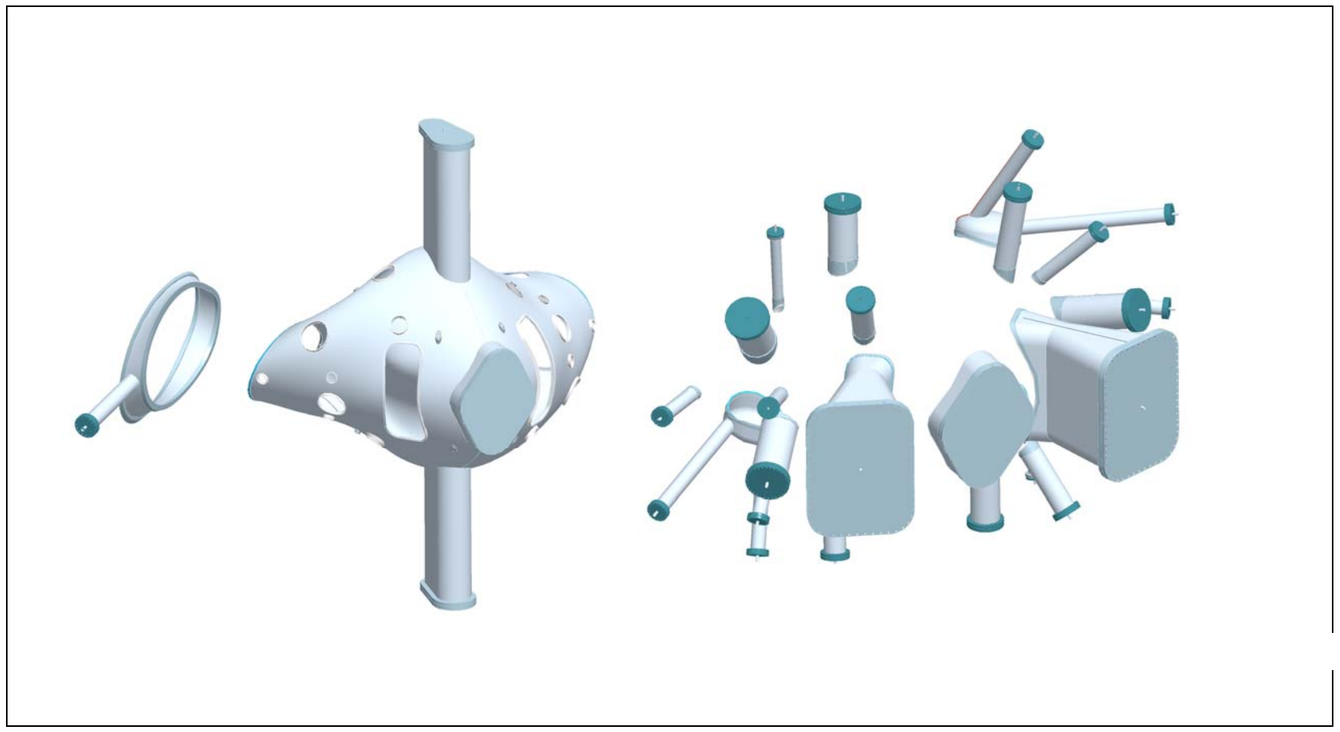


Modular Coil Prototype Point Cloud Overlaid on CAD Model

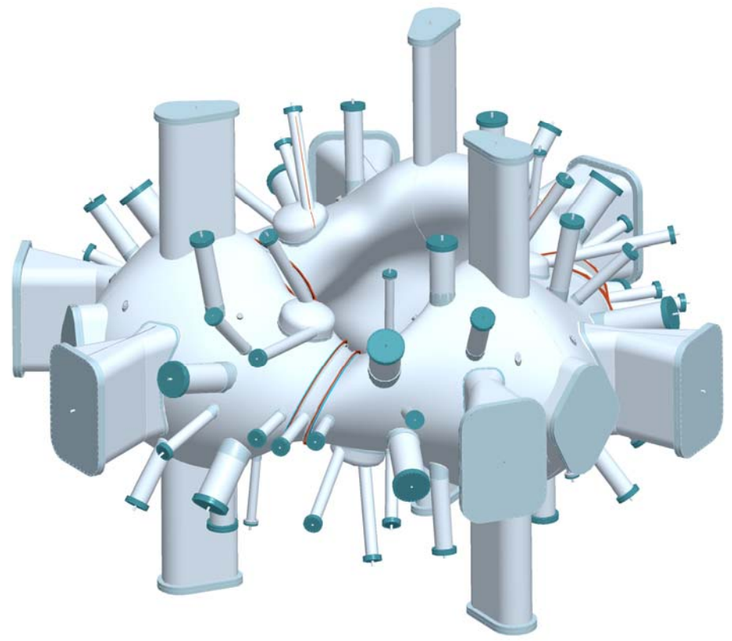
- Multi link Coordinate Measuring Machines (CMM) used to create “point cloud” scaled 3D representation of data.
- Overlaid on CAD model and analyzed.

- The finished VV prototype was within the specified +/- 4.2 mm.
- The winding form casting shell wall mostly varied + / - 3.8 mm. (Tolerance: + / - 6.4 mm). Largest variation was + / - 7.1 mm. Ample material to machine to final dimensions in all but a few minor regions.

Phase III Manufacturing of the Vacuum Vessel Is Underway



Contract is for (3) sets of the components shown above



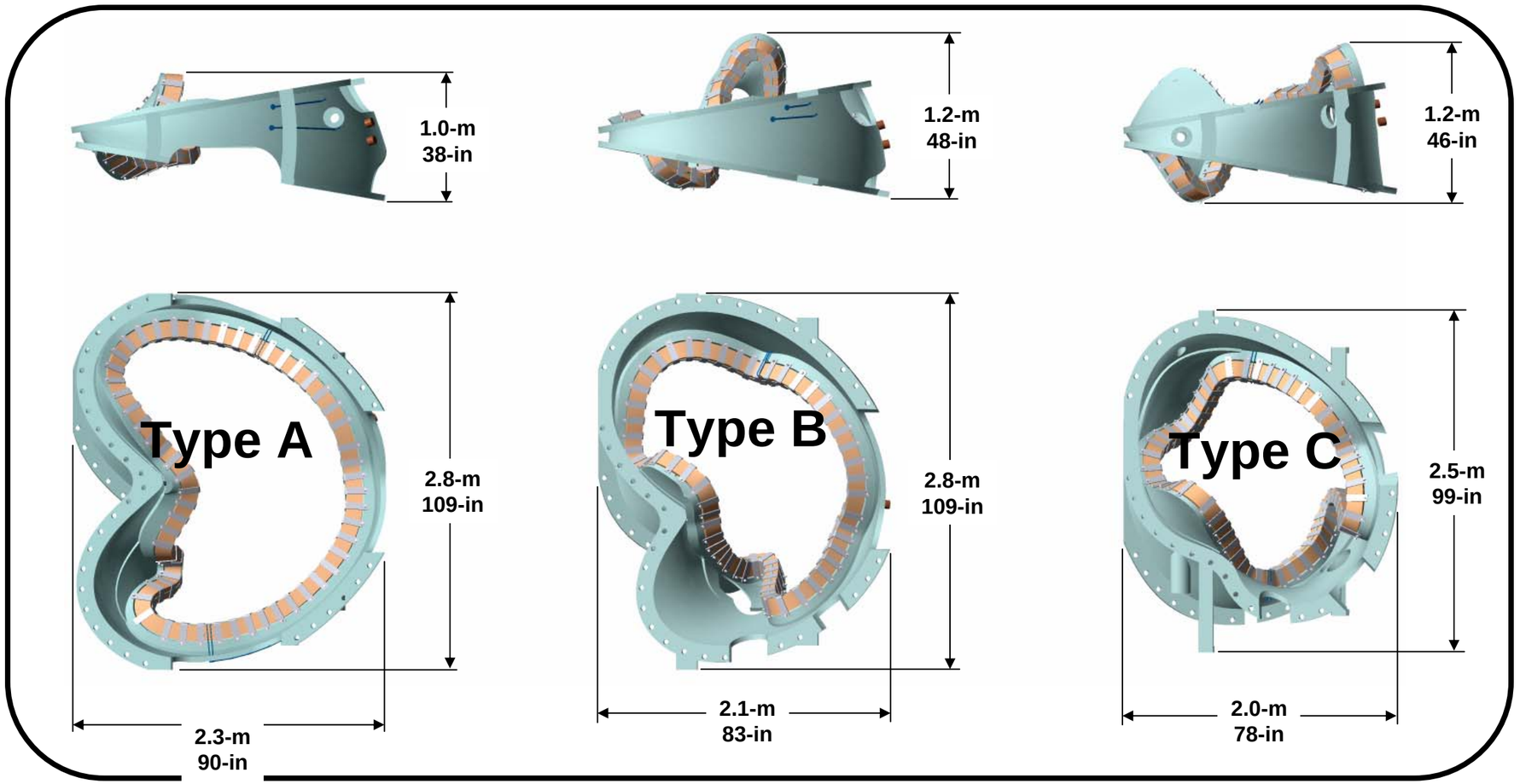
Vacuum Vessel / Port Assembly for Reference

- A subcontract for $4.5 M was awarded to Major Tool and Machine, Inc. in September, 2004.
- All of the vessel components are scheduled for delivery in the fall of 2005.

Phase III

Manufacturing of Modular Coil Winding Forms Is Underway

- An $8 M subcontract was issued to a team[1] led by Energy Industries of Ohio, Inc. of Independence, Ohio in October, ’04.
- (6) of each will be manufactured.
- The first winding form is scheduled for delivery in May, ‘05, and the final (18th) by August of ‘06.

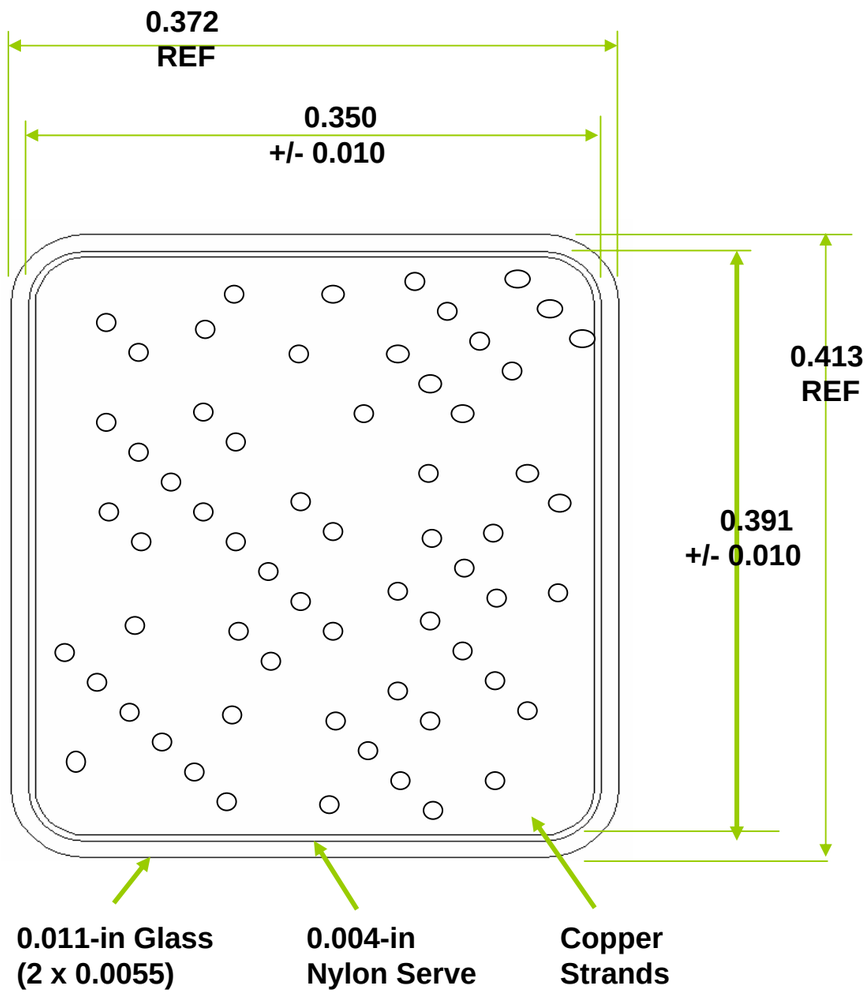


NCSX’s Three Modular Coil Winding Types

[1]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.

Phase III

The Flexible Conductor Is Being Manufactured



- **A contract for 48,000 feet of copper rope conductor was awarded to New England Wire Technologies of Lisbon, NH.**
- **First delivery is scheduled for December 2004**
- **Balance of delivery in March 2005**

Conclusions

- The three-phase manufacturing development program NCSX adopted to reduce technical, cost, and schedule risks for the complex, highly shaped components of NCSX has been largely successful.
  - Through early industrial involvement, NCSX has been able to identify and successfully address the challenging aspects of the design. *The designs developed are within the state-of-the art of industry*.
  - The prototyping phase was extremely productive:
    - R&D and prototyping activities at PPPL resolved the weak areas of the winding and vessel designs identified by the Phase I industrial studies. This allowed concurrent engineering of the vessel and modular coils in a timely manner.
    - The industrial vessel and winding form prototypes prototypes provided the confidence necessary for the subcontractors to enter into firm fixed price and schedule contracts.
  - **We look forward to receiving production components, beginning in May, 2005.**