Modular Coil Fabrication And R&D Activities

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and the PPPL/ORNL NCSX Team

NCSX Performance Baseline Review

Presentation Outline

- Risk Mitigation Plans- Modular coil fabrication
- What are the plans and goals for the R&D/Fabrication Prep phase of the NCSX project?
- How was safety incorporated into our daily planning and work activities for the R&D activities?
- Discuss specific R&D activities and results
- Discuss the fabrication of Modular coils
  - Tooling
  - Winding facility
  - VPI process
- Discuss cost and schedule

Risk Mitigation Plans

- *Risk mitigation for the fabrication of the Modular coils is being handled through an extensive R&D program that has been on-going since the CDR. Critical activities include:*
  - Development of a VPI plan for epoxy impregnating the modular coils
  - Perform conductor "Keystone" testing to determine what tolerance control can be obtained
  - Develop experience in winding compacted copper cable conductor through the use of prototype windings
  - Fabricate a full scale prototype coil.
    - Using prototype casting and final manufacturing processes
    - Verify the integrity of winding equipment
    - Train lead personnel for production winding program
    - Develop procedures and Safety requirements

R&D/Fabrication Preparation- Plans and Goals

- *Develop a sound plan for the fabrication of the NCSX Modular coils through design, testing and prototyping.*
  - Selection of epoxy resin, conductor and insulation scheme
  - Study of tolerance control (Keystone tests)
  - Development of epoxy impregnation "VPI" plan
  - Development of Manufacturing Process and Quality Assurance plan
  - Design/fabrication of coil manufacturing tooling and equipment
  - Wind and VPI prototype coils to gain experience and develop procedures

NCSX R&D – Safety is Integrated in All Aspects

- Safety is an important part of the PPPL culture and was incorporated in all aspects of the development program- This will carry over to production
- Job Hazard Analysis **(JHA's)** were developed
- Personnel protective equipment **(PPE's)** being used
- Involvement of all safety groups especially Industrial Hygiene (IH) who participated as a member of the weekly design/status meetings

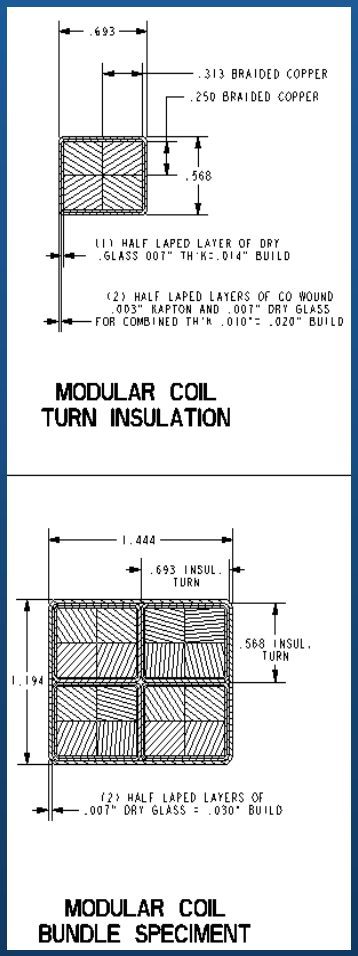
Epoxy Selection

- **Resin System selected- CTD-101K *(Well characterized for ITER)***
  - Product of *Composite Technology Dev. Inc.*
  - 3- Component epoxy system
  - Excellent performance at cryogenic temperatures with a long pot life and low viscosity
  - **Cure Cycle**
  - 5 hours @ 100 ° C (Cure)
  - 16 hours @ 125 ° C (Post cure)
- **Pot Life:**
  - 145 hours @ 25° C…… 1300 Cp viscosity
  - 60 hours @ 40° C…… 400 Cp viscosity*
  - 20 hours @ 60° C…… 100 Cp viscosity

GOOD WORKING TIME!!!

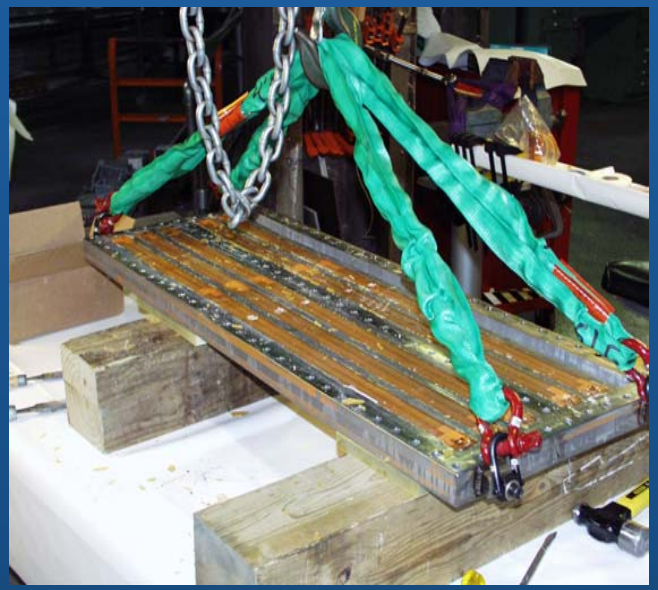
R&D- Conductor Performance Properties

NCSX



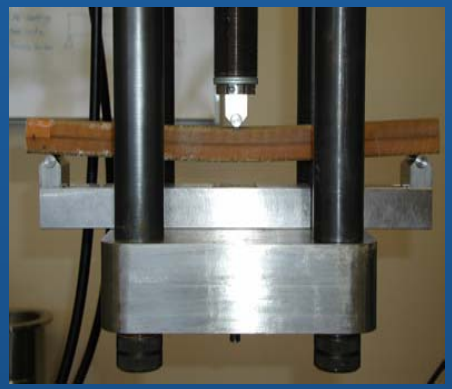
- The NCSX Project has contracted with Composite Technology Development Inc. (CTD) to perform both mechanical and thermal tests on impregnated conductor samples using the "CTD-101K" resin system selected for impregnating the Modular Coils.
- Single conductor used for samples ~ (4) 0.250 x 0.3125 " cables bundles together
- Single conductor and 4 conductor bundle specimens were provided to CTD by PPPL
- Tests included tensile, compression, flexural, thermal expansion

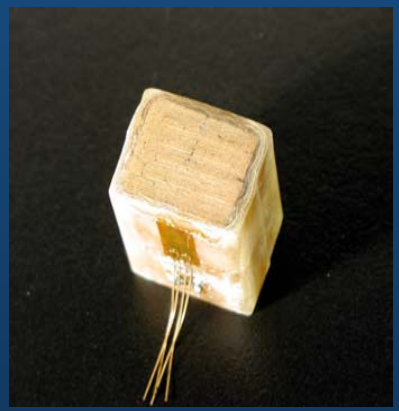
Single and 4-Conductor Specimens



R&D- Conductor Performance Properties

- Tests were performed at four temperature ranges (76, 100, 150 and 295 K)
- Test results have been consistent with our expectations showing higher strengths at lower temperatures
- Additional testing needs to be completed at room temperature to complete the data curves.





R&D- New Conductor Performance Properties

- Additional tests are being planned using the final cable conductor and insulation scheme. [PDR Recommendation]
  - Test Plan: In addition to the previous mechanical and thermal tests. Additional shear and fatigue testing will be included. [PDR Recommendation]
  - New conductor [final conductor] has been procured and will be delivered in late December 2003. Both standard process and non-lubricated conductors have been procured and will be tested and compared. [PDR Recommendation]
  - New insulation scheme: The new turn insulation scheme consists of 0.004 in. thick nylon serve plus (2) 1/2 lapped layers of 0.004 in. S-2 glass
- The sample preparation as well as testing will be performed in-house at PPPL.
- ***These results are key inputs to the detailed thermal/stress analyses of the windings which are currently underway.***

Copper Rope Conductor

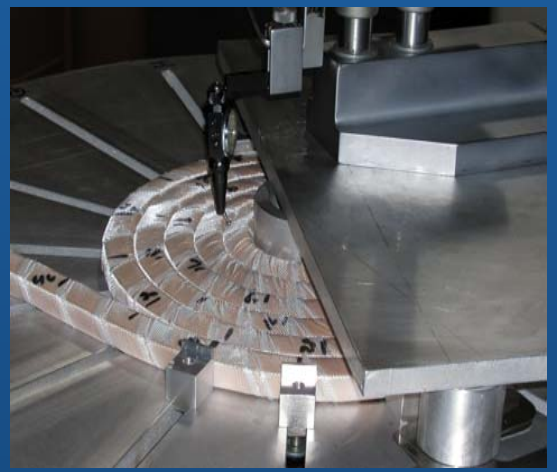
NCSX

- All conductors were fabricated using copper rope that was compacted to required dimensions (tolerance +/- 0.010")
- Material: OFHC copper per ASTM B-577
- Nylon serve was used on all but the #2 conductor evaluated (minimizes loose strands)

Type	Conductor Size	Tolerance	Ga.	Dia. (in.)	CMA	Bunch #1	Bunch #2	Bunch #3	Cable
1	0.500 in. x 0.625 in.	+/- 0.010 in.	36	0.005	300,000	(68) @ 1.5 in. RHL	(3) @ 3 in. RHL	(5) @ 3 in. RHL	(12) @ 6 in. LHL
2a	0.250 in. x 0.3125 in.	+/- 0.010 in.	32	0.008	290,000	(25) @ 1.5 in. RHL	(7) @ 3 in. RHL		(7) @ 6 in. LHL
2b	0.250 in. x 0.3125 in.	+/- 0.010 in.	32	0.008	290,000	(25) @ 2.0 in. LHL	(7) @ 4 in. LHL		(7) @ 4 in. RHL
3	0.539 in. x 0.660 in.	+/- 0.010 in.	34	0.006	336,729	(101) at 3 in. RH	(7) @ 5.5 in. RHL		(12) @ 6 in.LHL
4	0.539 in. x 0.660 in.	+/- 0.010 in.	34	0.006	336,729	(101) at 3 in. RH	(7) @ 5.5 in. RHL		(9) @ 6 in.LHL
						(101) at 3 in. LHL	(7) @ 5.5 in. LHL		(3) @ 6 in.RHL
5	0.539 in. x 0.660 in.	+/- 0.010 in.	34	0.006		(101) at 3 in. RH	(7) @ 5.5 in. RHL		(9) @ 6 in.LHL
						(101) at 3 in. RH	(7) @ 5.5 in. RHL		(3) straight center
6	0.350 in. x 0.391 in.	+/- 0.010 in.	34	0.006		(44) @ 2.5 in. RHL	(5) @ 3 in. RHL		(9) @ 3.5 in. LHL
									(3) @ 3.5 in. RHL

Keystone Conductor Trials

- Bench top trials were performed on the various conductor samples



- ***Due to their complex geometry the use of compacted copper conductor is essential in manufacturing the NCSX Modular coils***
- **Findings - Winding tests using compacted conductor:**
  - **Conductor has a tendency to swell with every bend, twist or general handling**
  - **Some reshaping is possible however the dimensional swelling cannot be retrieved**
  - **Less insulation and smaller cross section reduces the degree of Keystoning**
  - **Conductor deviations due to Keystoning in single conductor were approximately 0.010 in**
  - **Nylon serve provides conductor stability and minimizes copper splinters T/T**

Keystone Findings: Four- Cable Conductor

Four-cable conductor

- Originally selected to minimize Keystoning due to small cross-section

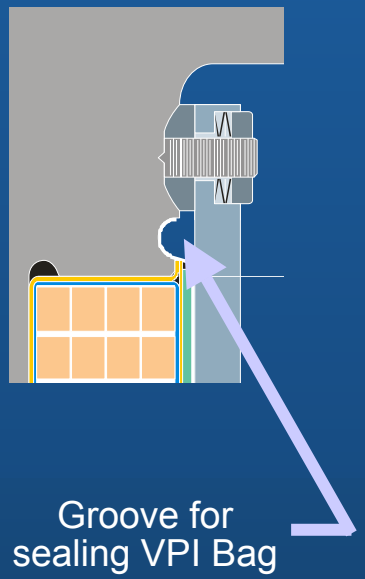
- ***Four-cable conductor, not to be confused with the 4-in-hand conductor scheme was found to be unacceptable.***

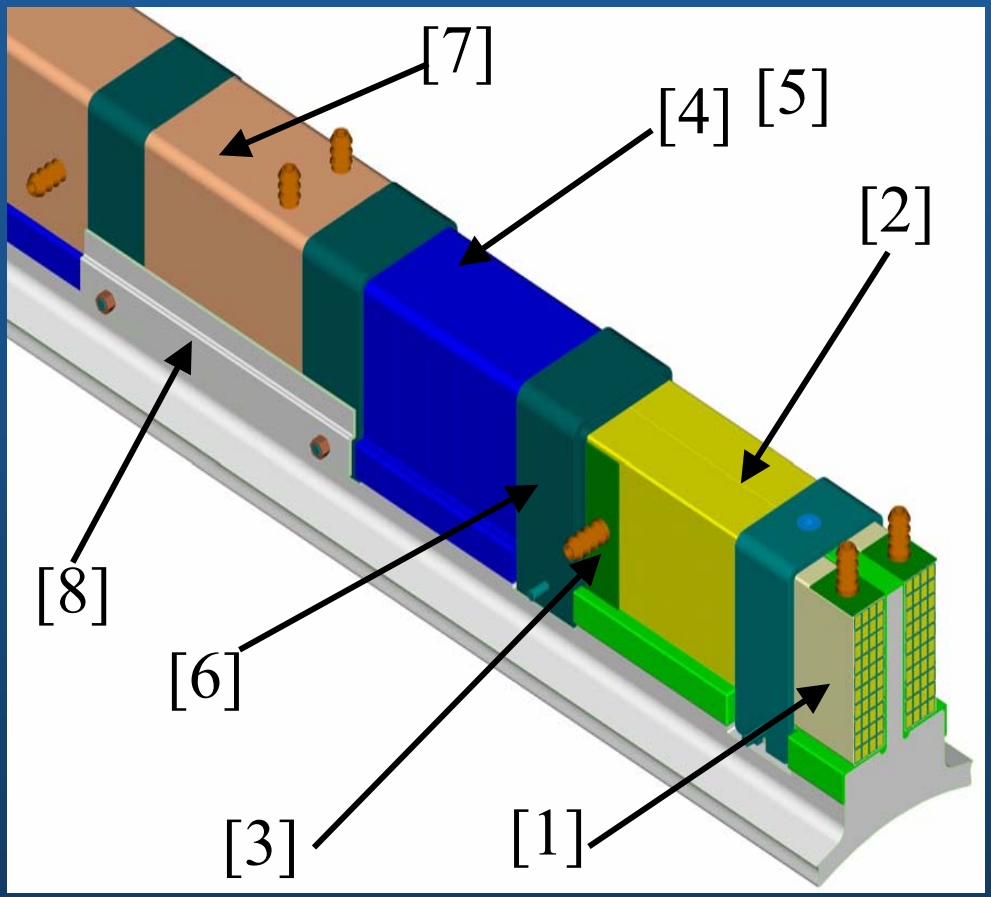
- **Findings:**
  - **Extreme distortion and twisting of the individual copper ropes occurred under the insulation**
  - **Conductors could not slip relative to each other.**
  - **Conductors would have to be hand insulated just inches from the winding surface- (labor intensive/not practical)**
  - **Conductor too limp to be automatically insulated using taping machine**

Keystone R&D Findings

- New insulation scheme, eliminates the Kapton and extra glass thickness in the T/T insulation which helps to minimize keystoning
- Rolling or pre-forming of conductor is not a realistic option, due to the complex and changing geometry of the coils
- Use smaller conductor to minimize Keystoning
- ***Between the conductor tolerance +/-0.010 in. and dimensional variations due to keystoning, reproducibility would be difficult without compensating with the use of shimming***
- Proposed method for winding modular coils
  - **Wind approximately 6 –8 inch length of pre-insulated conductor**
  - **Set conductor in place by gently hand tapping in place**
  - **Measure position of turn using "Faro-arm" plus specially designed tools**
  - **Shim as required to maintain tolerance control**

NCSX Modular Coil Mold Assembly

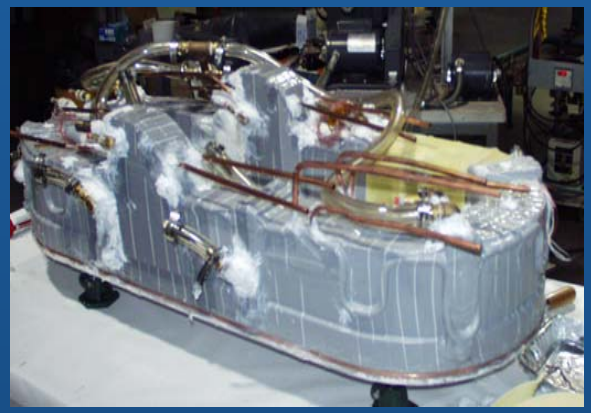




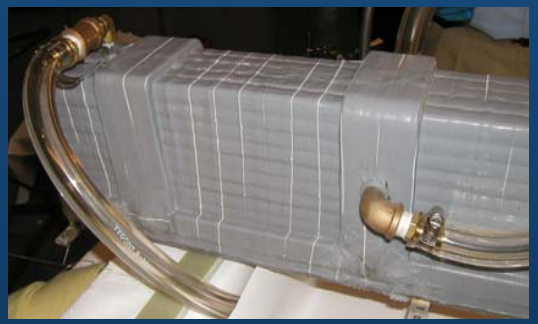
- Install coil ground wrap [1]
- Install copper cladding [2]
- Install G-10 sprues [3]
- Install (2) Layers silicone rubber tape mold [4]
- Paint mold with 2-part RTV (several layers) [5]
- Install final coil clamps [6]
- Install epoxy impregnated felt between the clamps [7]
- Install strong backs between clamps [8]

R&D- Development of VPI Process

- Development of a sound plan for epoxy impregnating (VPI) the Modular coils was a high priority for NCSX
- The modular coils due to the complex geometry will be VPI'd in the vertical position.
  - Complex geometry steered the project towards developing non-welded vacuum tight mold jacket. (based upon TFTR PF coil experience- "Bag Mold") ***This has been a success.***
  - Bag mold requires the use of an autoclave to minimize pressure differentials
  - General procedure for filling coil has been developed and demonstrated (small scale)

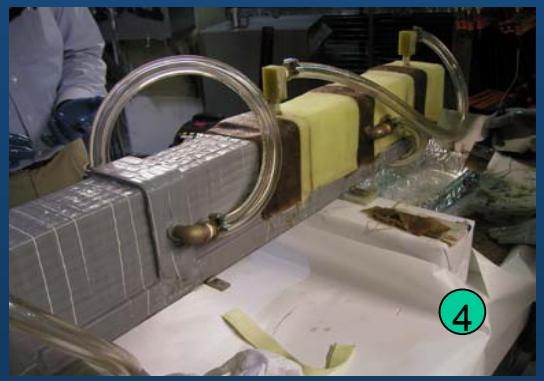


Racetrack Coil

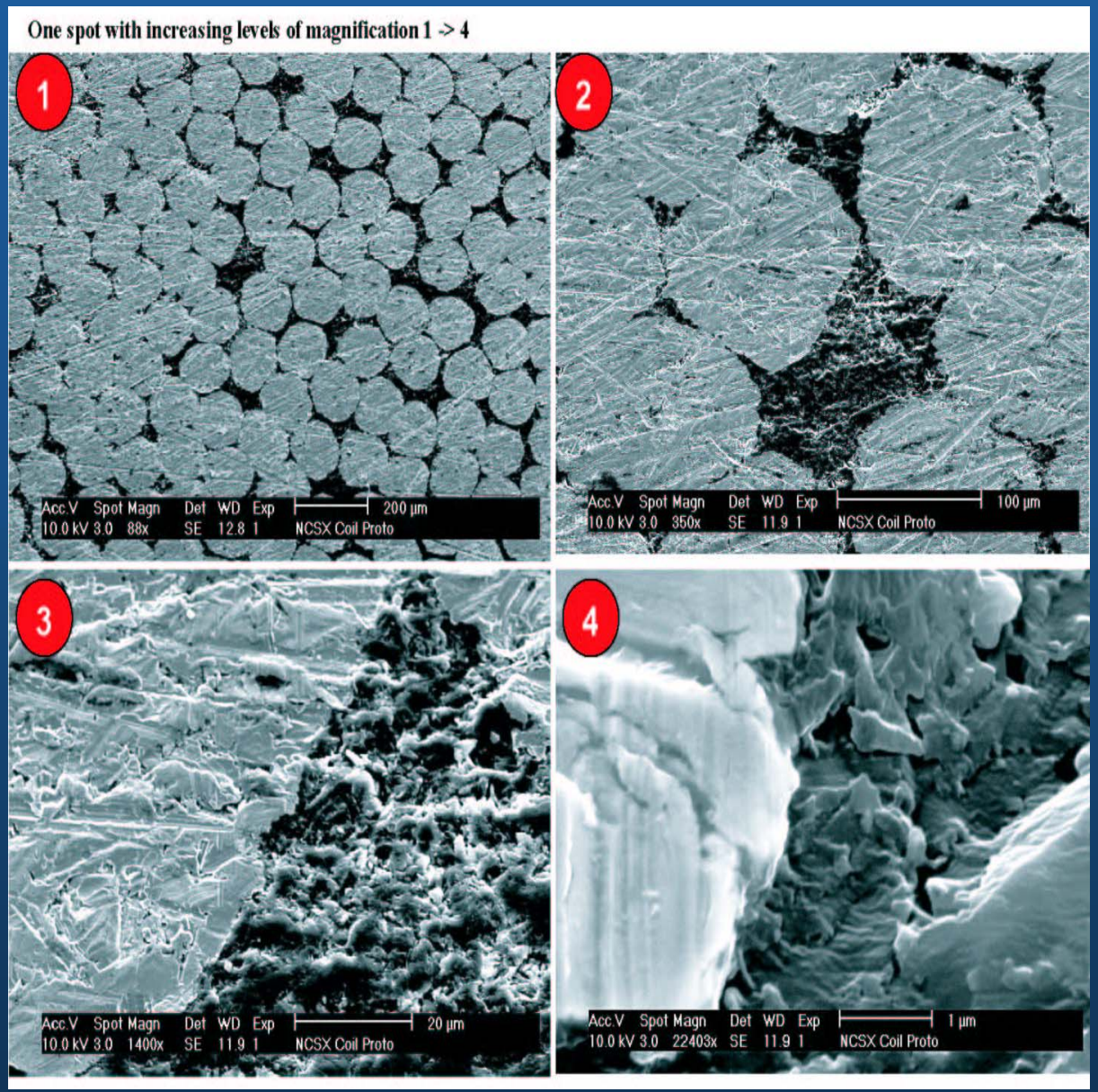


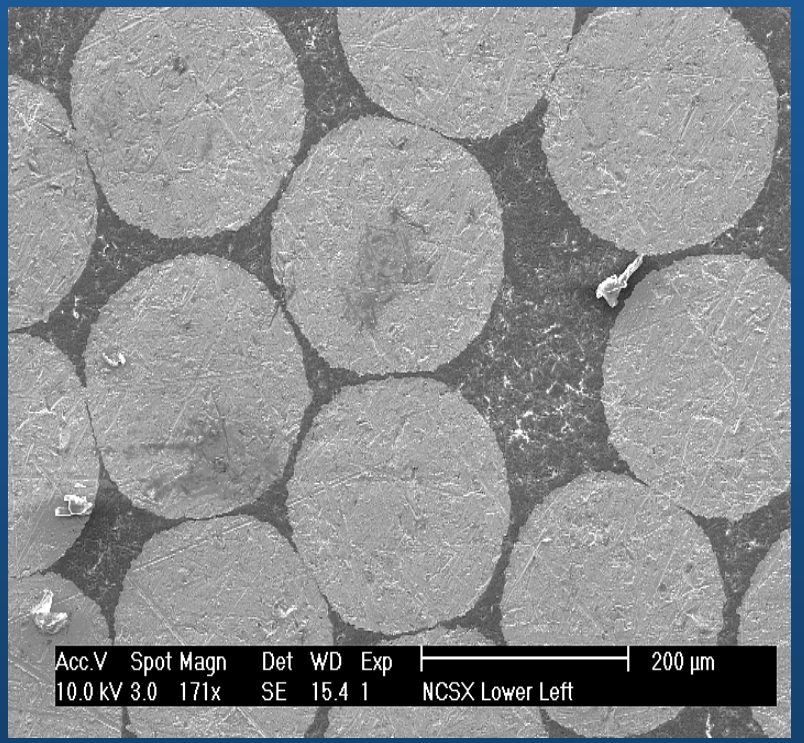
Straight Tee

NCSX R&D- Straight Tee Section



NCSX R&D- Conductor VPI Trials





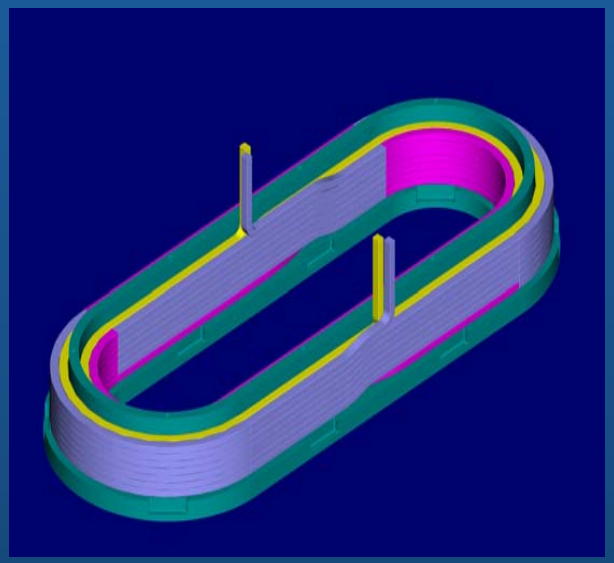
Electron Microscope photos show good epoxy penetration between strands

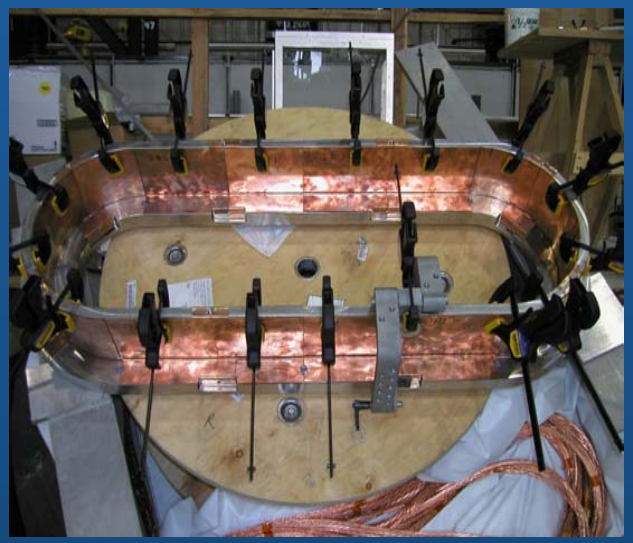
Additional R&D VPI Trials

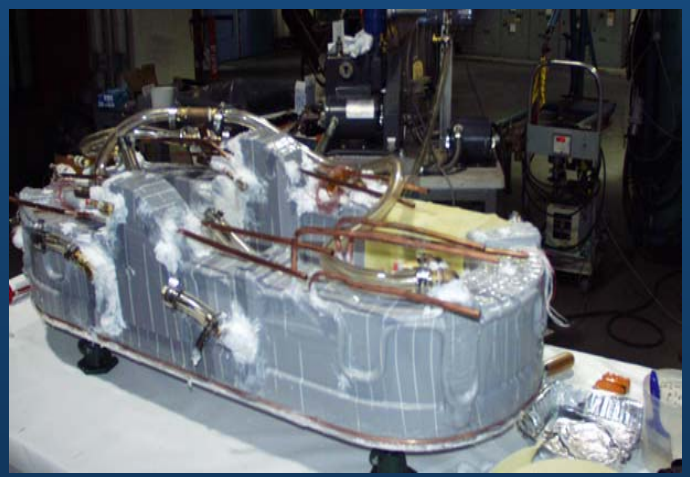
Epoxy impregnated Univ. of Tenn. Racetrack Coil

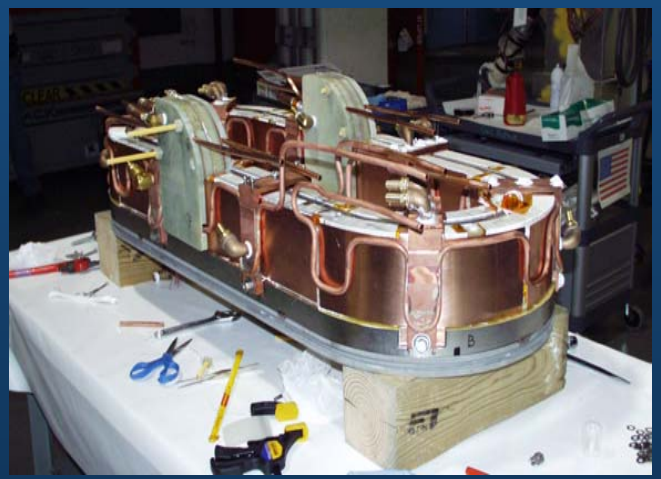
Wound and epoxy impregnated Racetrack Coil at PPPL

R&D- Winding Racetrack Shaped Coil



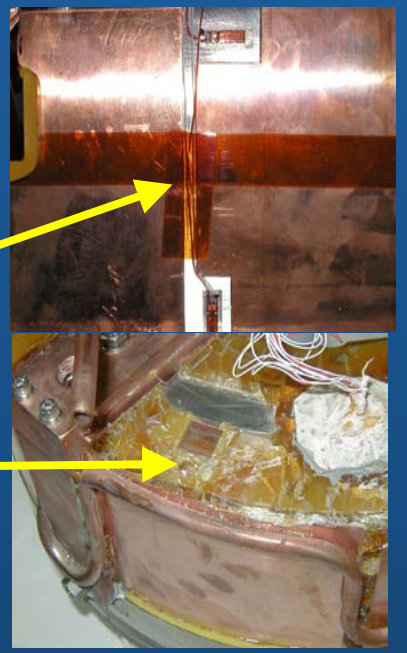




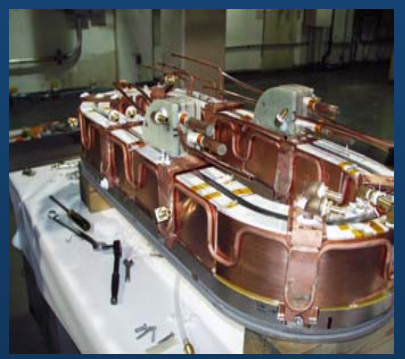


R&D- Winding Racetrack Shaped Coil

- Racetrack coil
  - 1st. Opportunity to wind a coil using the compacted copper conductor- gained invaluable experience (0.539 in. X 0.660 in.)
  - Coil had typical cross-section of Modular coil
  - Instrumented with stain gauges and thermocouples to provide test feed-back
  - Removable nylon plugs were installed to inspect shrinkage between impregnated coil and stainless winding form
  - First use of copper cladding for cooling



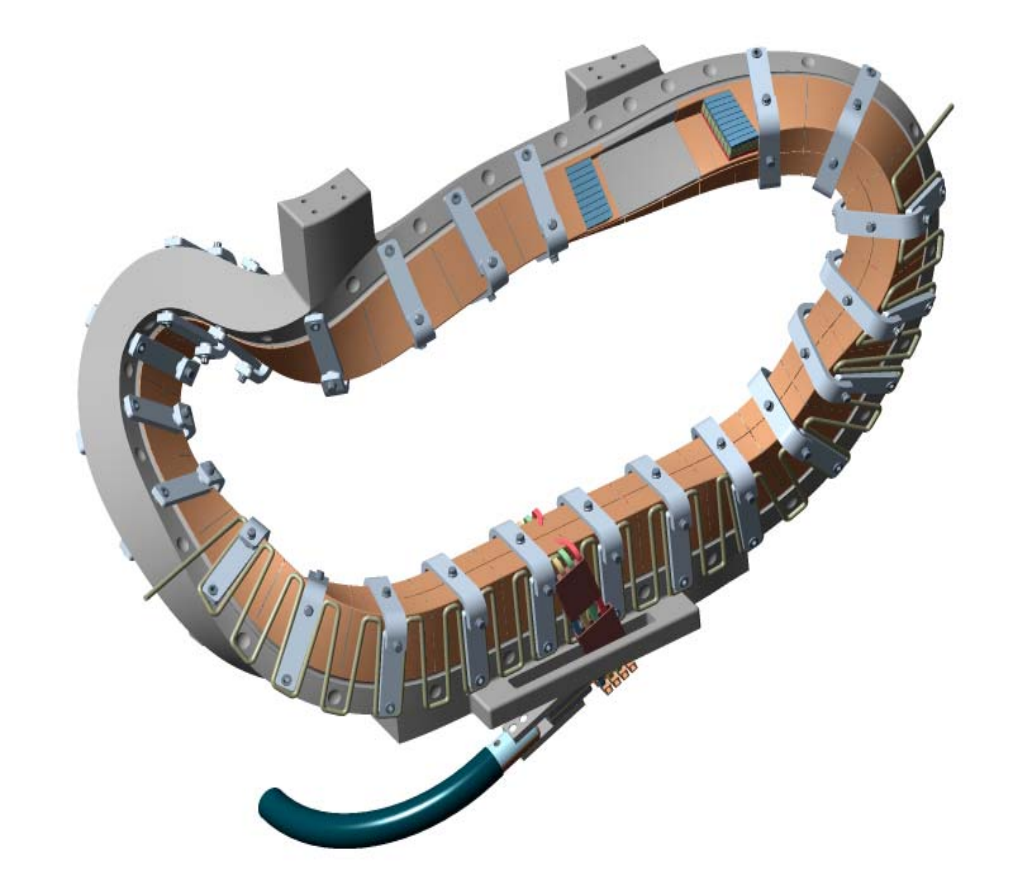
- Performance of the Racetrack coil is being evaluated at liquid nitrogen temperatures (Initial tests were successfully performed at ORNL, with the final full power modular coil tests to be performed at PPPL)



Remaining R&D Activities

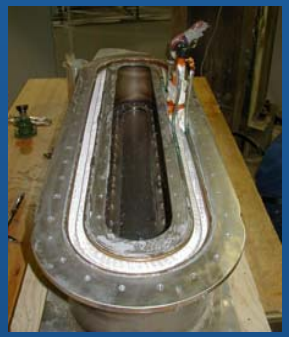
- Complete epoxy/conductor mechanical and thermal property tests (including fatigue) using final modular coil conductor and insulation scheme
  - Evaluate std. process vs. additional cleaning processes for conductor
  - Verify that impregnated conductor properties agree with preliminary data
- Demonstrate winding and metrology techniques on (2) twisted windings
- Wind and VPI a full scale prototype coil. Coil to be fabricated in the NCSX manufacturing facility, located in the vacated TFTR Test Cell.
  - Verify the integrity of winding equipment
  - Train lead personnel for production winding program
  - Develop procedures and Safety requirements

Fabricate and test "twisted" racetrack shaped coil



- **Twisted coil will capture many physical features of the NCSX Modular coils including:**
  - Mod coil Cross-section and Transitions
  - Conductor and Insulation scheme
  - Lead arrangement
- **Coil will be instrumented with strain gauges and thermocouples to monitor coil conditions**
- **Coil will be used to demonstrate/learn:**
  - shimming to control tolerance
  - Issues of fabrication using similar features of modular coil
  - Final "Bag Mold" configuration
  - Coil performance under cold condition at full modular coil power
  - First use of Autoclave

Evolution of R&D Winding / VPI Development



Univ. of Tenn. Coil

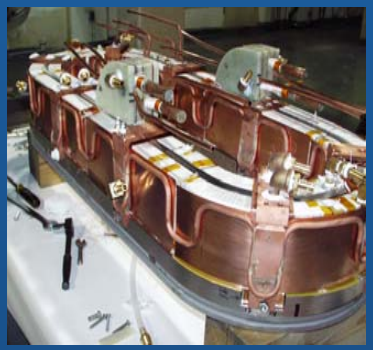
First use of CTD-101K epoxy system for VPI

COMPLETE

Straight Tee Section

First use of "Bag Mold" for VPI

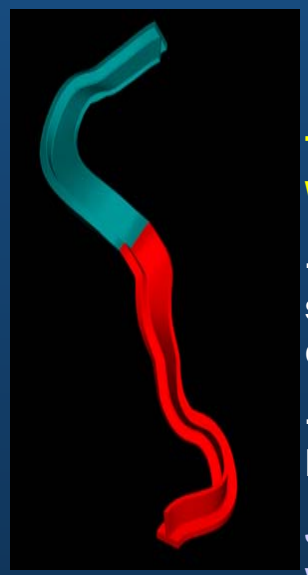
COMPLETE



Racetrack Coil

First winding experience & use of copper cladding

COMPLETE being tested

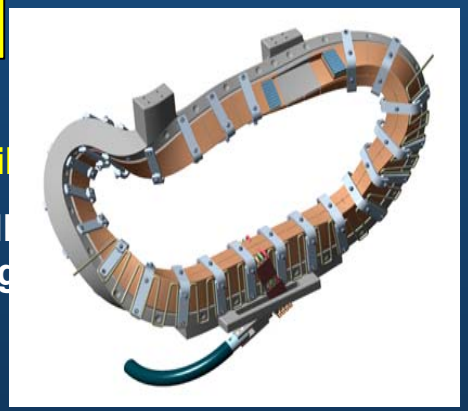


Twisted Vertical Winding

-First use of shimming to control tolerance

-First use of 4 in hand conductor

Jan. 04 Start winding



Twisted Racetrack

-Final coil lead configuration

-First use of autoclave for VPI

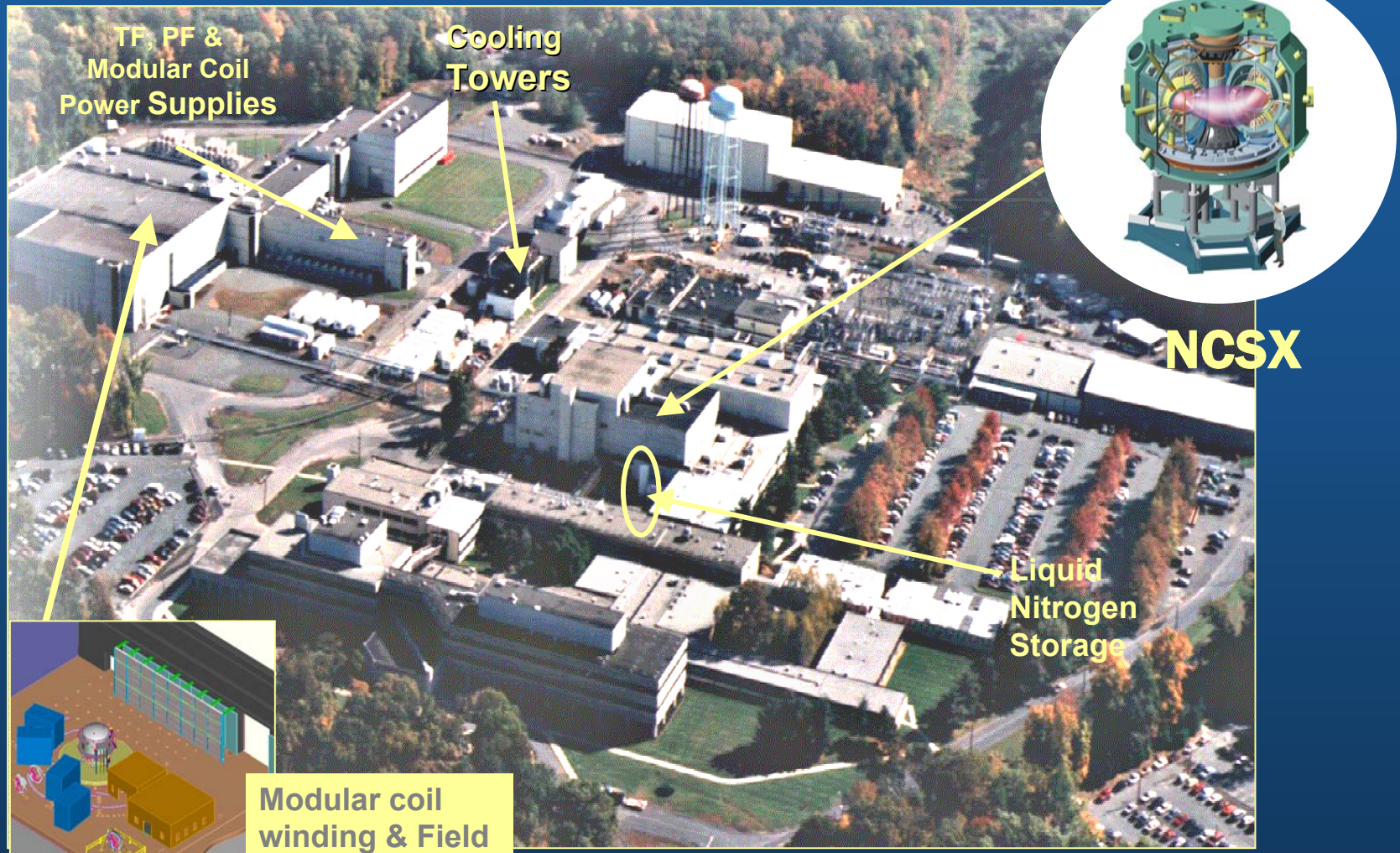
March 04

Full Scale Prototype Coil

First use of all manufacturing processes

June 04

Modular Coil Fabrication



Modular Coil Success

➢ **KEY**

to successfully producing NCSX Modular Coils

Accurately machined castings

Adequate clamping of turns during winding

Knowledgeable oversight during fabrication

Shimming allowance for tolerance control

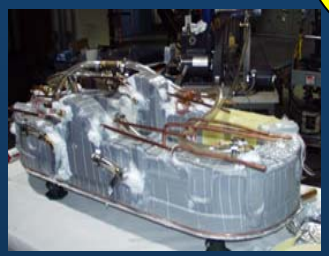
Cleanliness

Clean winding room conditions

Good insulation & VPI System

Decades of experience in:

- ➢ Coil manufacturing
- ➢ VPI/epoxy related activities
- ➢ High voltage testing

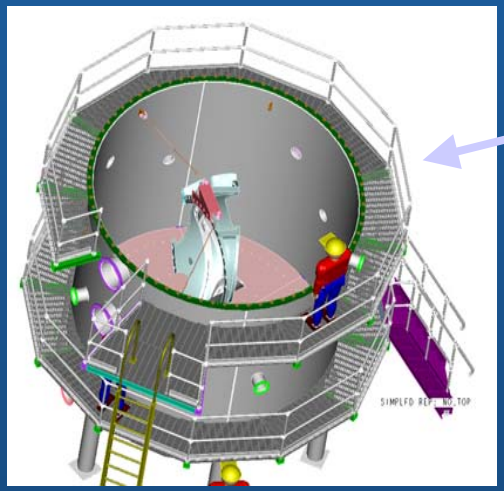


R&D and Testing program to finalize these requirements

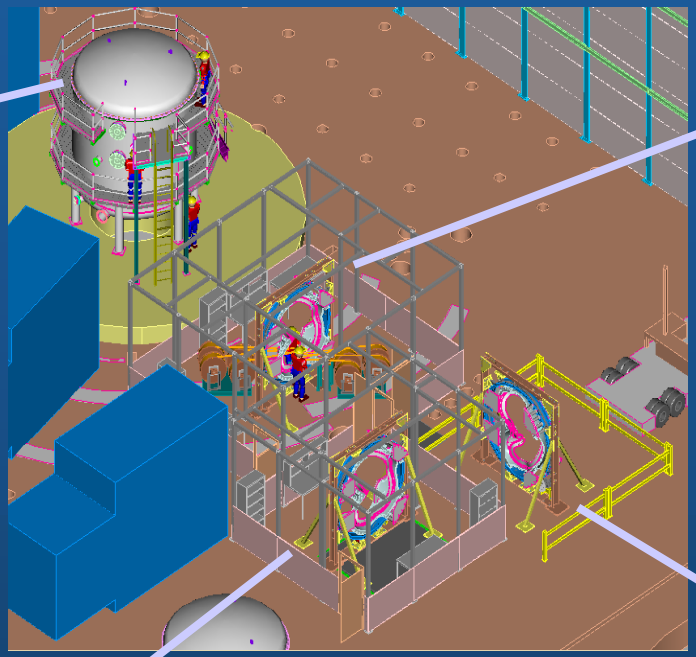
Modular Coil Fabrication

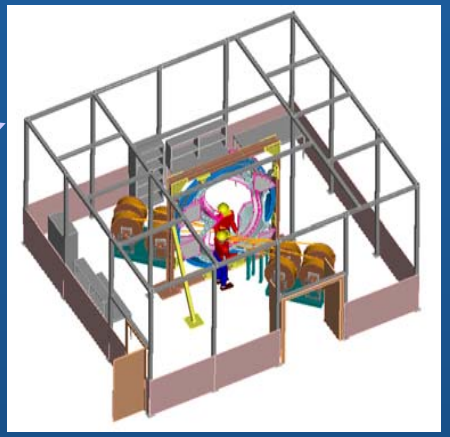
- The Modular coils will be fabricated in the D-site TFTR Test cell
- One winding station will be used
  - Prototype and 1st. production coil (one shift operation)
  - 2nd. Thru 18th. Production coils (2 shift winding operation)
- The winding and mold stations will be located in enclosed rooms where cleanliness can be controlled.
- The coils will vacuum-pressure-impregnated (VPI) in an autoclave
- Maintain coil current center tolerance of +/- 0.020 inches by shimming between turns

D-site Coil Manufacturing Facility

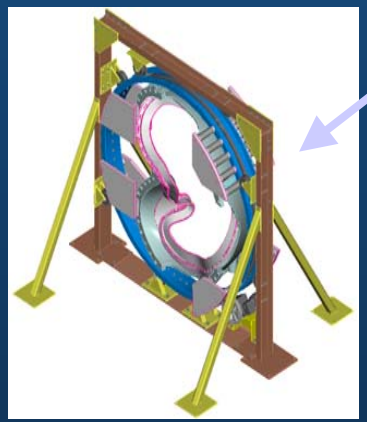


Station #4 VPI (autoclave)





Station #2 Coil Winding

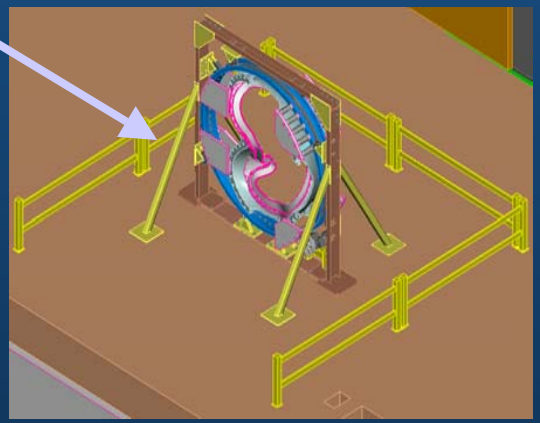


Station #3

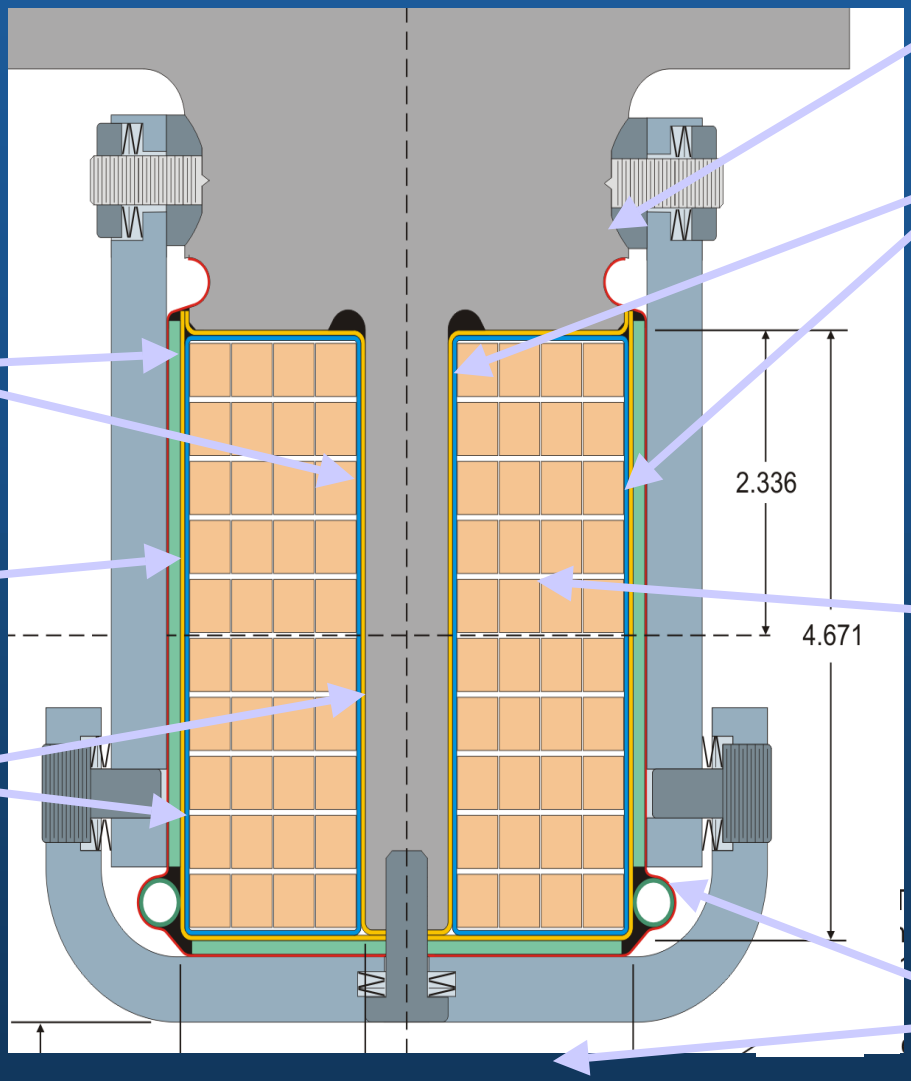
Mold/VPI Preparation

Station #1

Casting Preparation



Modular Coil X-Section



Groundwrap ~ 0.030 " S-2 glass plus 0.008" Kapton

G-10 spacer

Diagnostic loops- Inner and outer wall

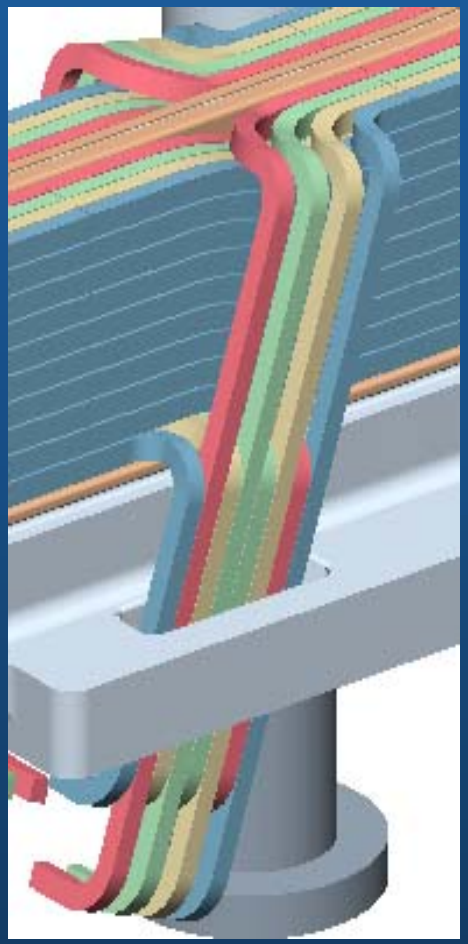
Bag Mold Groove

Copper cladding and cooling lines- inner and outer walls

- Wind compacted copper conductor (10 layers x 4 in hand)

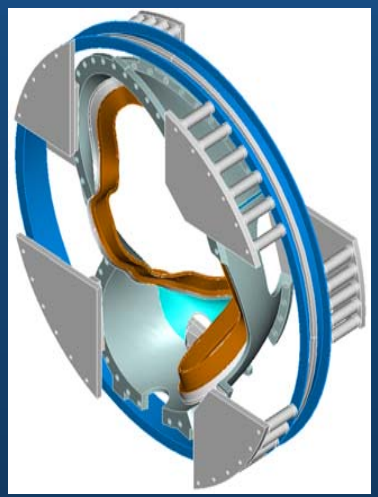
Coil clamp

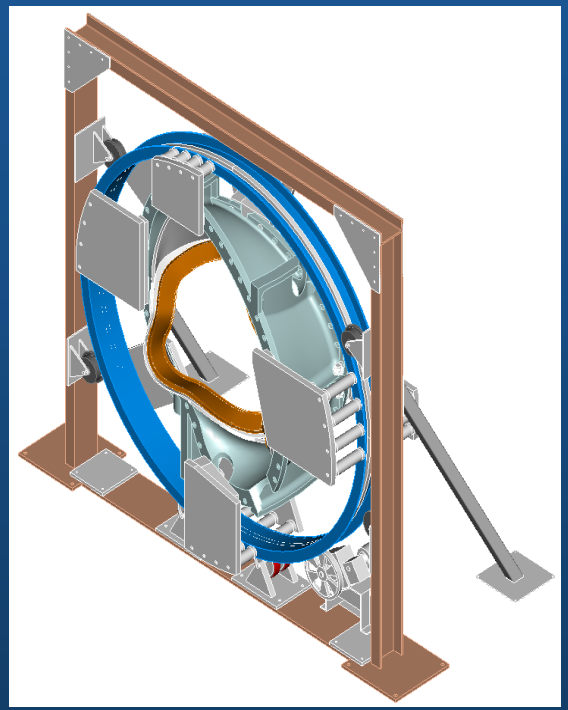
Modular Coil Manufacturing



- **Compacted copper conductor will arrive pre-insulated.**
  - 0.004 in. nylon serve
  - (2) ½ lapped layers of 0.004 in. dry S-glass
- **Coil layers will be wound 4 conductors in-hand**
- **The upper and lower leads will join together and run along the side of the coil bundle and through the casting**
- **Leads will be terminated outside the casting [First demonstrated on "Twisted racetrack coil"]**

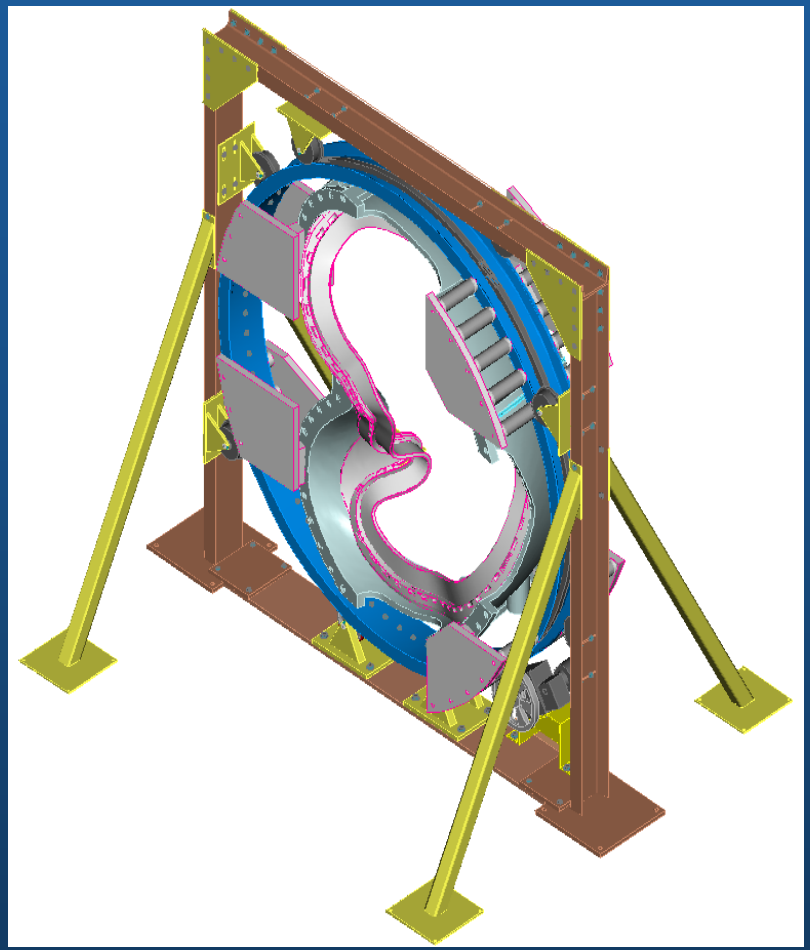
Coil Turning Fixtures





- Design of vertical turning fixture will accommodate all (3) types of modular coils
- Turning fixture be used at three stations (Casting Preparation, Winding and Mold Preparation)
- Allows easy work access to both sides of casting
- Motor and gear driven

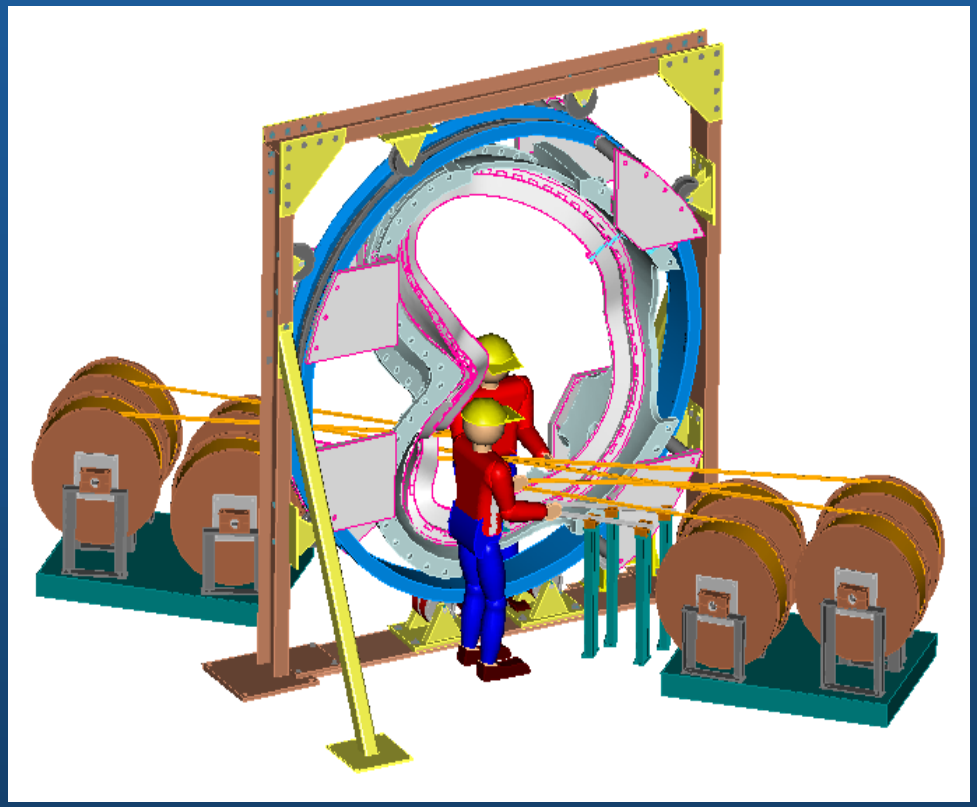
Casting Preparation Station #1



- **Station #1 Activities**
  - Receipt inspect castings
  - Mount casting to support ring
  - Install studs for winding and coil clamps
  - Clean casting
  - Install inner chill plates
  - Install inner diagnostics

Duration: 12 days per coil (1 shift)

Coil Winding Station #2

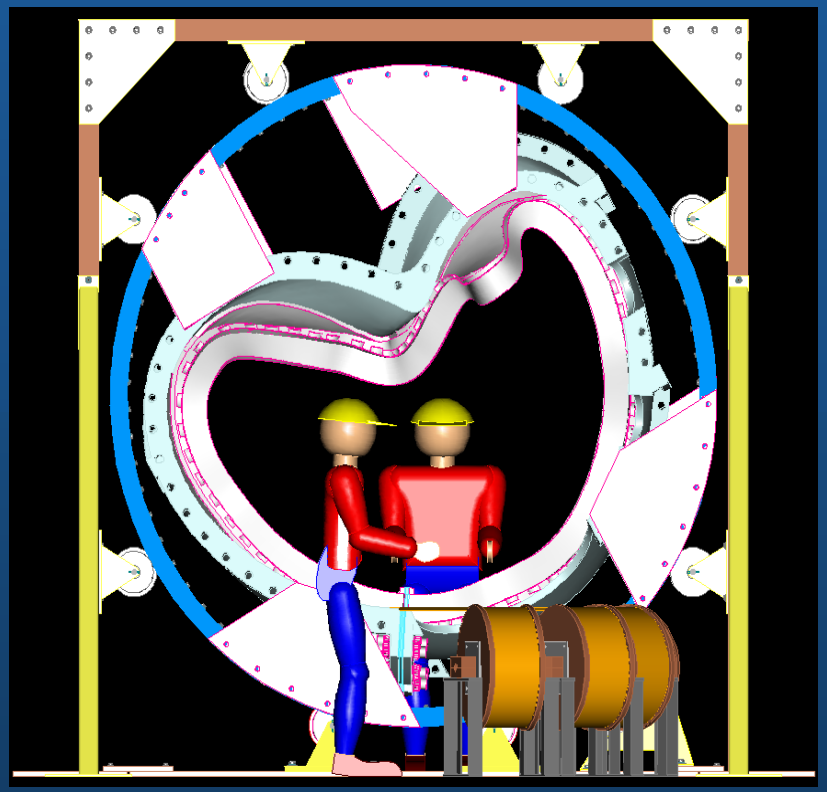


- **Station #2 Activities**
  - **Install winding clamps**
  - **Install inner ground wrap insulation**
  - **Position leads**
  - **Wind turns on side A** (4-in-hand x 10 layers)
  - **Position and secure leads**
  - **Repeat process for side B**
  - **Complete ground wrap insulation**

Duration per coil: 38 days (1 shift) - coil #1

19 days (2 shifts) – coils #2-18

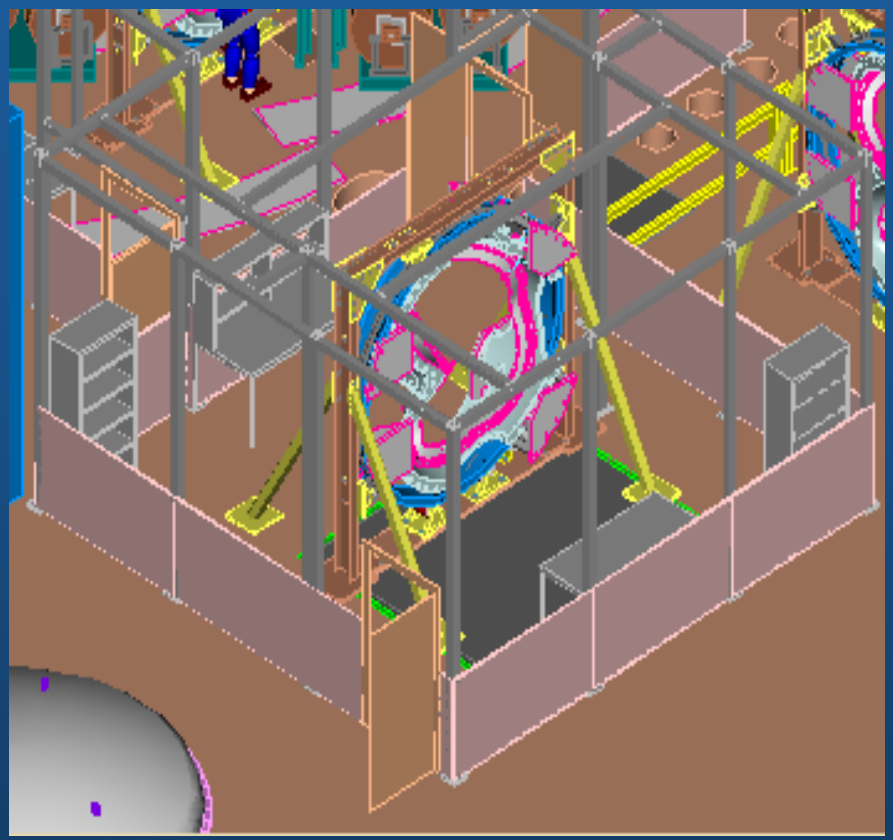
Coil Winding Station #2



Conductor spool height will be variable to accommodate change in winding height

Winding clamps developed to secure turns in place during winding operations.

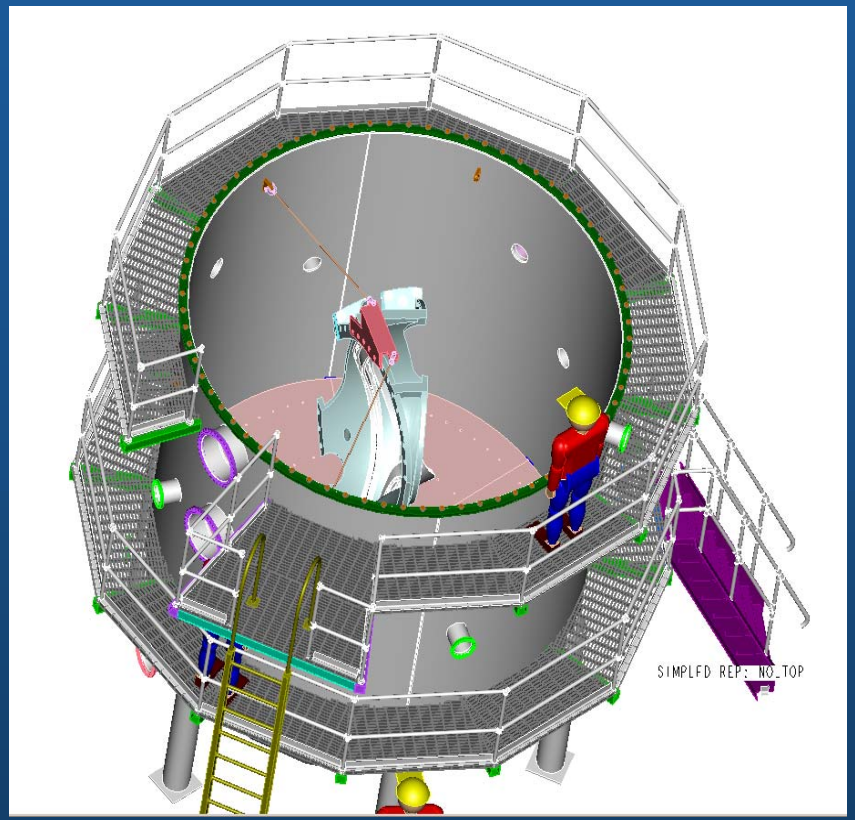
Molding/VPI Preparation Station #3



- **Station #3 Activities**
  - Install external chill plates
  - Install external diagnostics
  - Install bag mold
  - Install final coil clamps
  - Pressure test cooling lines
  - Leak check mold assembly
  - Install epoxy shell

Duration per coil : 15 days (1 shift)

VPI Station #4

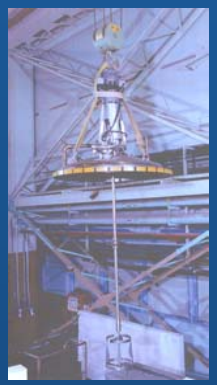


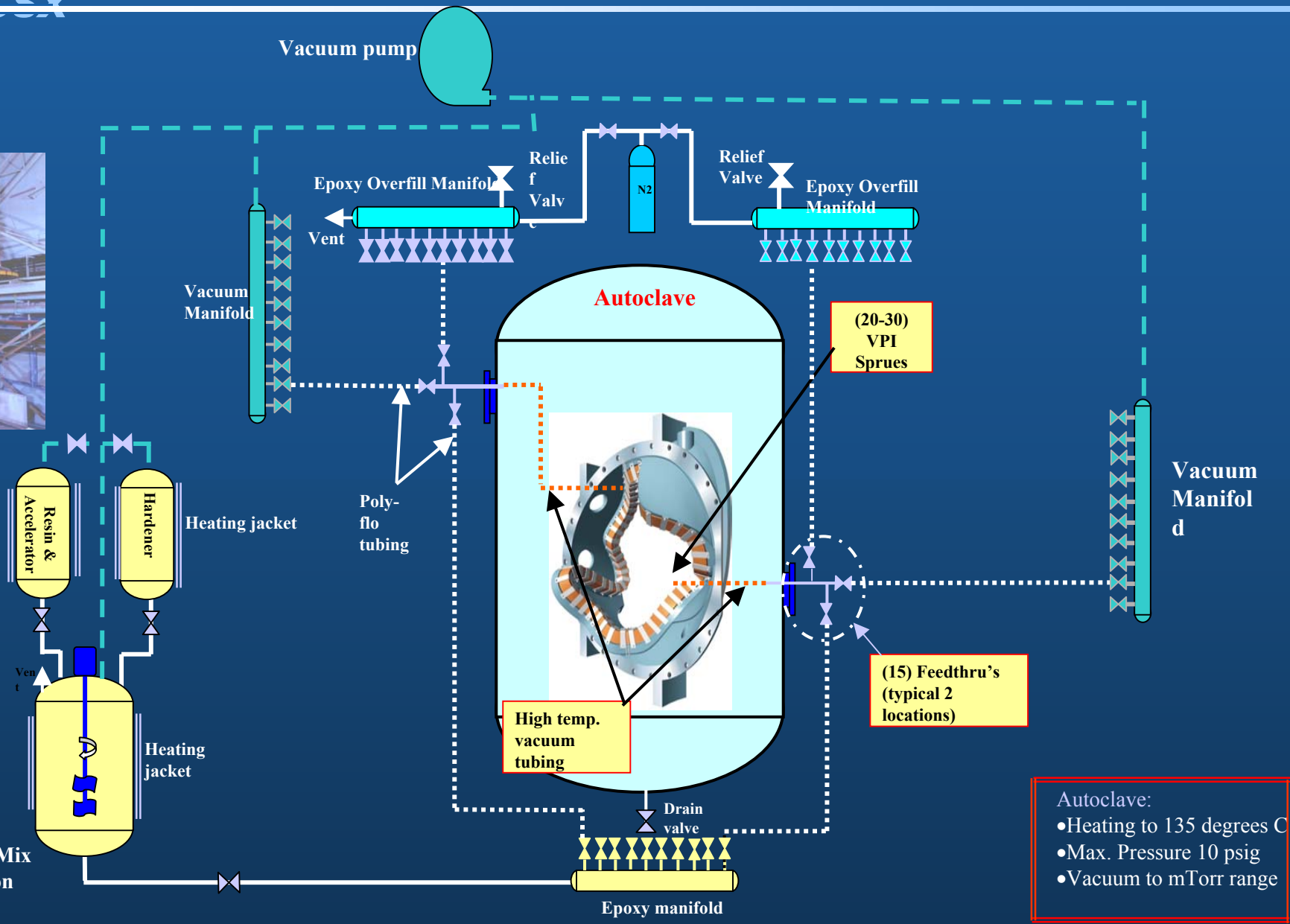
- **Station #4 Activities**
  - Install Modular coil into autoclave
  - Connect fill lines, manifolds
  - Hookup thermocouples
  - Leak check mold assembly
  - Vacuum impregnate modular coil
- **Station #5 Activities**
  - -Transport to test station for cleanup and final test (warm test conditions)

Duration per coil (station #4): 12 days

Duration per coil (Cleanup & test#5): 5 days

Modular Coil VPI Flow Diagram

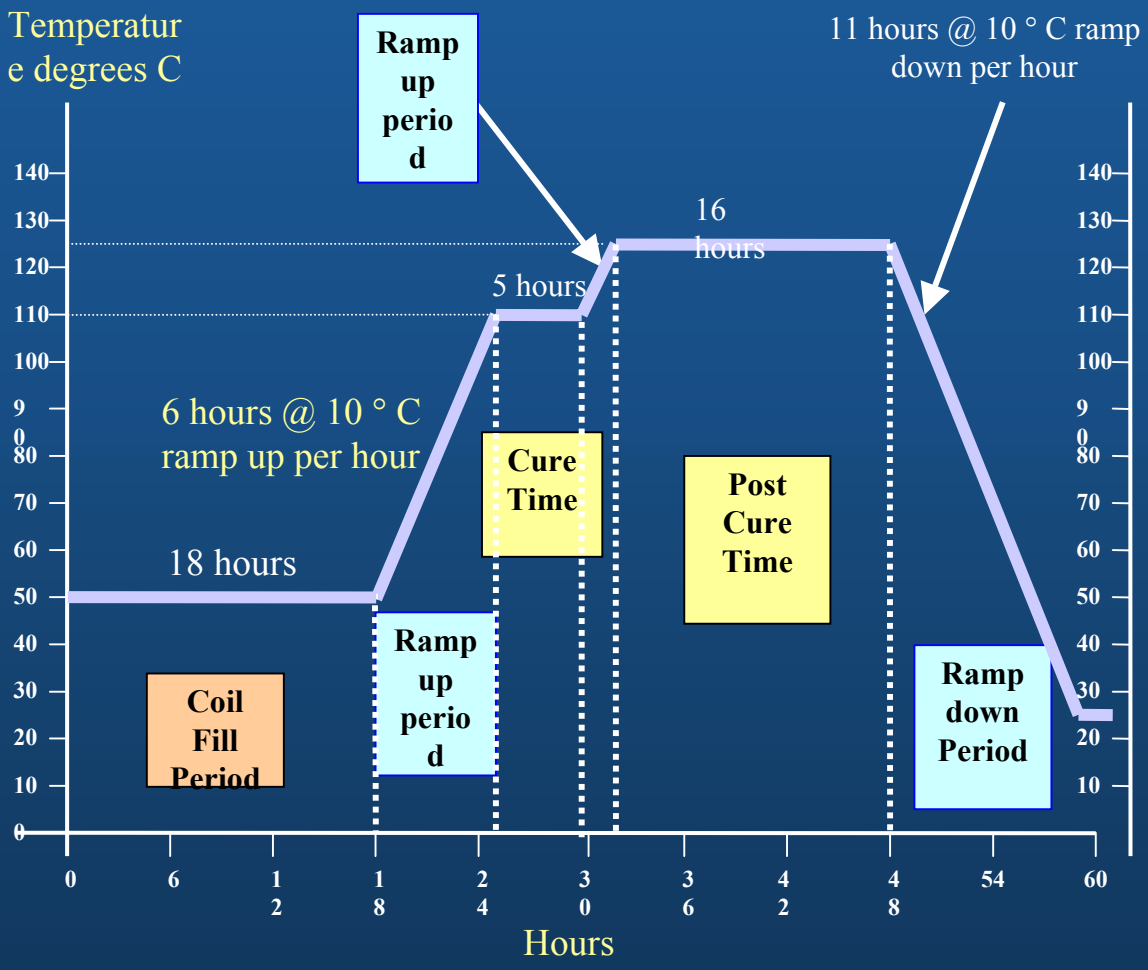




Autoclave:
- Heating to 135 degrees C
- Max. Pressure 10 psig
- Vacuum to mTorr range

NCSX MODULAR COIL VPI CYCLE

Epoxy component mixing



Viscosity measurements

"Scrambled Egg" test to verify Gel temperature

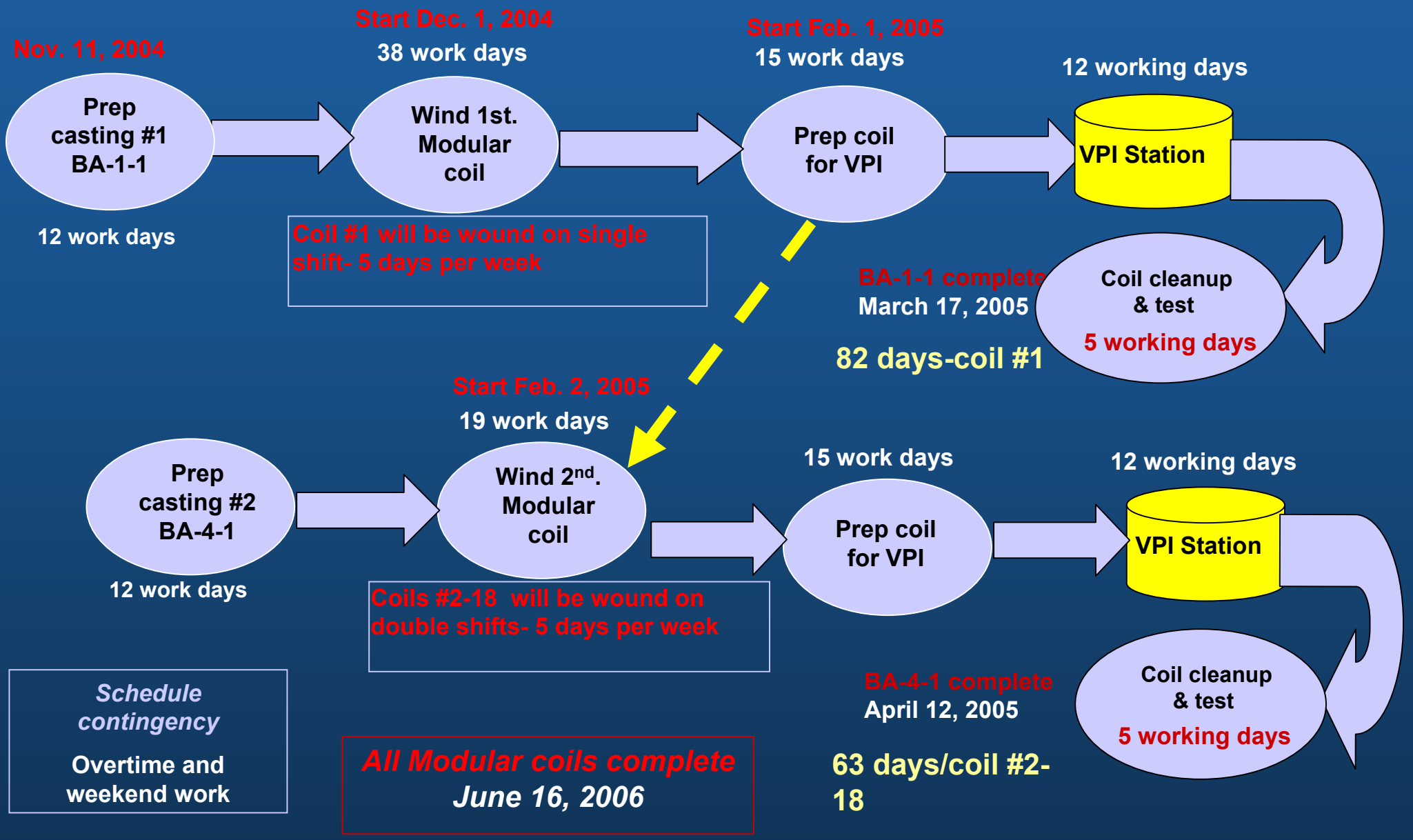
Cost and Schedule Estimates

NCSX

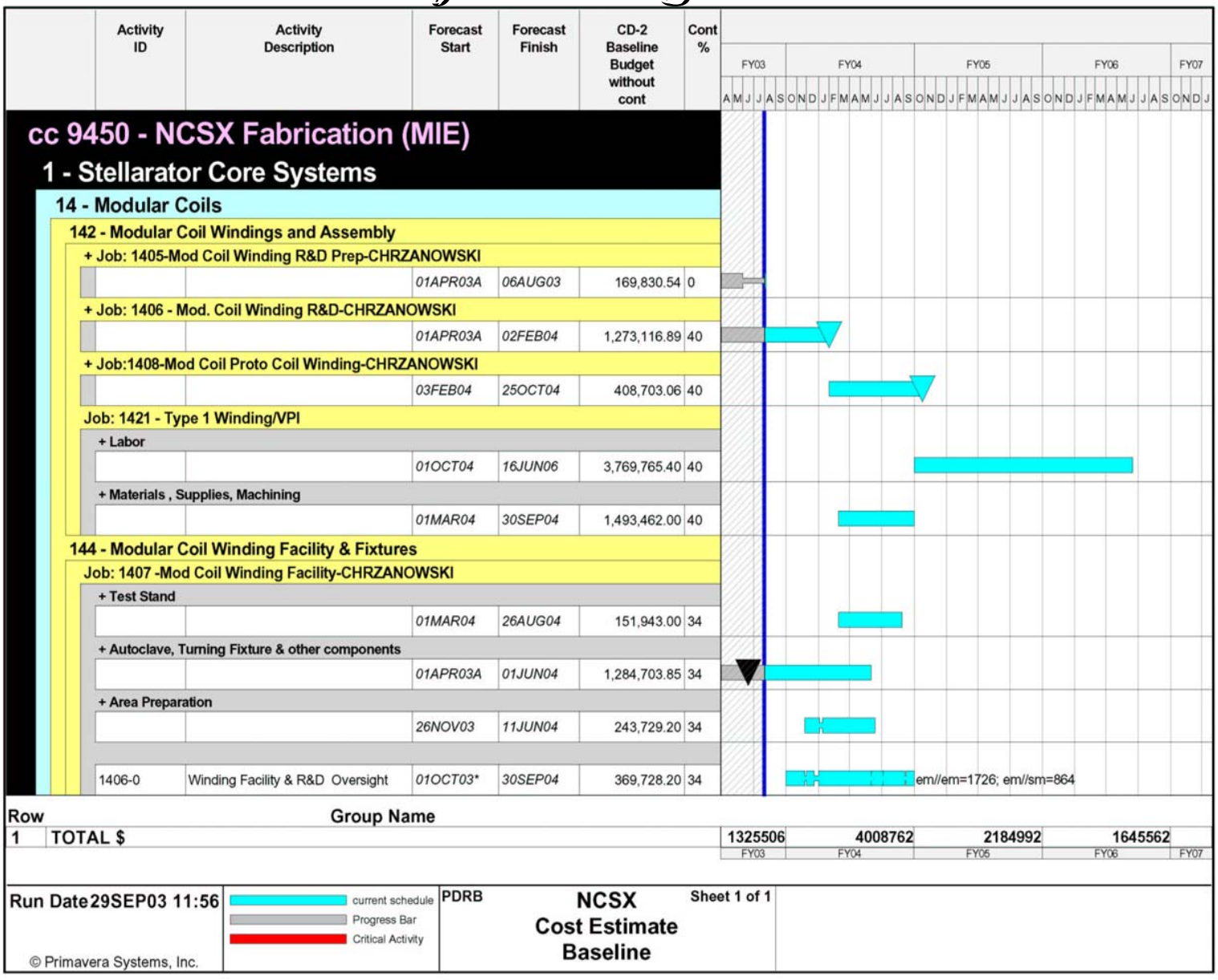
- Estimates were based upon past winding experience, findings from R&D activities plus material estimates from outside industry.
- Winding estimates were broken down to individual activities as shown in the example below.

Task No.	TASK DESCRIPTION	Working Days	Shifts per day	No. of Tech.	No. of man-hours
3	**Station No. 3- Coil Winding**	**38**	**Total working days 1st. coil**		
3	**Prepare winding station for winding pancake #1**	**5**			**128**
	Install coil in turning fixture	1	1	4	32
	Install winding clamps	2	1	3	48
	Position inner groundwrap insulation onto winding form	2	1	3	48
	Note: The first coil will be wound on 1 shift. Coils 2 thru 18 will be wound on (2) shifts				
3	**Wind pancake #1**	**14**			**336**
	Position & secure 1st. coil lead set	2	1	3	48
	Wind layer #1 - [10] turns of conductors onto casting	10	1	3	240
	(4-in-hand)				0
	Position & secure 2nd. coil lead set	2	1	3	48
3	**Prepare station for pancake #2**	**3**			**72**
	Reposition winding equipment	1	1	3	24
	Position groundwrap insulation onto winding form	2	1	3	48

Modular Coil Manufacturing Schedule



Cost & Schedule - R&D and Manufacturing



Activity ID	Activity Description	Forecast Start	Forecast Finish	CD-2 Baseline Budget without cont	Cont %
cc 9450 - NCSX Fabrication (MIE)					
1 - Stellarator Core Systems					
14 - Modular Coils					
142 - Modular Coil Windings and Assembly					
+ Job: 1405-Mod Coil Winding R&D Prep-CHRZANOWSKI		01APR03A	06AUG03	169,830.54	0
+ Job: 1406 - Mod. Coil Winding R&D-CHRZANOWSKI		01APR03A	02FEB04	1,273,116.89	40
+ Job:1408-Mod Coil Proto Coil Winding-CHRZANOWSKI		03FEB04	25OCT04	408,703.06	40
Job: 1421 - Type 1 Winding/VPI					
+ Labor		01OCT04	16JUN06	3,769,765.40	40
+ Materials , Supplies, Machining		01MAR04	30SEP04	1,493,462.00	40
144 - Modular Coil Winding Facility & Fixtures					
Job: 1407 -Mod Coil Winding Facility-CHRZANOWSKI					
+ Test Stand		01MAR04	26AUG04	151,943.00	34
+ Autoclave, Turning Fixture & other components		01APR03A	01JUN04	1,284,703.85	34
+ Area Preparation		26NOV03	11JUN04	243,729.20	34
1406-0	Winding Facility & R&D Oversight	01OCT03*	30SEP04	369,728.20	34

FY03 FY04 FY05 FY06 FY07

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Row	Group Name	FY03	FY04	FY05	FY06	FY07
1	TOTAL $	1325506	4008762	2184992	1645562	

Run Date 29SEP03 11:56

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current schedule
Progress Bar
Critical Activity

PDRB

NCSX Cost Estimate Baseline

Sheet 1 of 1

Approximate cost

$9.2 million

40% Contingency on remaining R&D plus winding tasks

34% Contingency on Test stand, tooling and area preparations

Impact of PDR Recommendations

- Several recommendations were made at the PDR. Those that were not already in our base plan are being evaluated:
  - Prototype & test modular coil leads- already included with Twisted Racetrack coil. (No schedule or $ impact)
  - Verify that cable preparation dry vs. lubricant does not effect epoxy/copper bonding- new copper conductor has been purchased to test dry vs. lubricated (no schedule impact with modest $ impact)
  - Continue winding and potting coil sections with multiple curvatures.- already planned in R&D program with twisted winding forms (No additional schedule or cost impact)
  - Develop and implement a plan to evaluate shear stress quality of the composite and fatigue properties. - Presently being planned. (No additional schedule impact but some $ impact)

Summary- Completions

- The R&D program has made great progress since the CDR; and has been able to provide the NCSX Project with needed information in the Modular Coil design. These activities include:
  - Tested the mechanical and thermal properties of the impregnated conductor
  - "Keystone test" have helped to define the conductor size, tolerance control and manufacturing processes
  - The development and demonstration of a sound "VPI" plan ("Bag Mold" and epoxy delivery method)
  - The outline of the manufacturing process plan has been developed
  - Experience gained in winding Racetrack shaped coil has helped to define the manufacturing plan

Summary- R&D and Manufacturing Preparations

- **Remaining R&D/ Manufacturing Activities Include:**
  - Completion of the epoxy/conductor mechanical/thermal tests
  - Fabricate and test (2) "Twisted winding forms including a coil
  - Fabricate tooling and setup of Modular coil manufacturing facility
    - Autoclave fabrication has begun
  - Generate a Modular coil Manufacturing, Inspection and Test Plan (MIT)
  - Fabricate and test the "Prototype" Modular coil
  - Address PDR recommendations
- ***Progress has been good, and completion of the NCSX Manufacturing & R&D tasks identified above will be completed safely, within budget and on schedule***