

Modular Coil Winding Fabrication

**J. Chrzanowski
and the NCSX Team**

**NCSX Final Design Review
for Modular Coil Winding Form**

Presentation Outline

NCSX

- Risk Mitigation Plans- Modular coil fabrication
- Safety
- Fabrication of Modular coils
 - Materials
 - “Inch Worm” and “Twisted Racetrack” coil trials
 - Tooling
 - Winding facility
 - VPI process
- Summary

Risk Mitigation Plans

NCSX

- *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
 - Verify new cooling scheme
 - Wind and VPI prototype coils to gain experience and develop procedures

NCSX R&D – Safety is Integrated in All Aspects

NCSX

- **Safety** is an important element of the PPPL culture and is incorporated in all aspects of the development program and will be carried over to production
- **Integrated Safety Management (ISM)**
- **Job Hazard Analysis** surveys (**JHA's**) are developed to identify hazards associated with the various tasks and the personnel protective equipment required
- **Involvement of all safety groups** in developing plans for manufacturing

Epoxy Selection

NCSX

➤ 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!!!**

Copper Rope Conductor

NCSX

➤ Conductor Specifications:

- OFHC copper- 34 AWG bare copper (0.0063 in. diameter) per ASTM B-577
- Tolerance ~ +/- 0.008 inch
- 3240 strands
- Cable construction:
 - (54) @ 2.5 in. RHL x (5) @ 3.5 RHL x (9) @ 5.5 in. LHL
 - (54) @ 2.5 in. LHL x (5) @ 3.5 LHL x (3) @ 5.5 in. RHL
- Conductor will be manufactured with no lubricants (clean)
- Conductors will be fabricated using copper rope that was compacted to required dimensions (tolerance +/- 0.008")
- Conductor will have 0.004 in. 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 0.004 in. thick S-2 fiberglass tape [0.004 in. center and 0.007 in. at edge- average build = 0.0055 in.]

Keystone R&D Findings

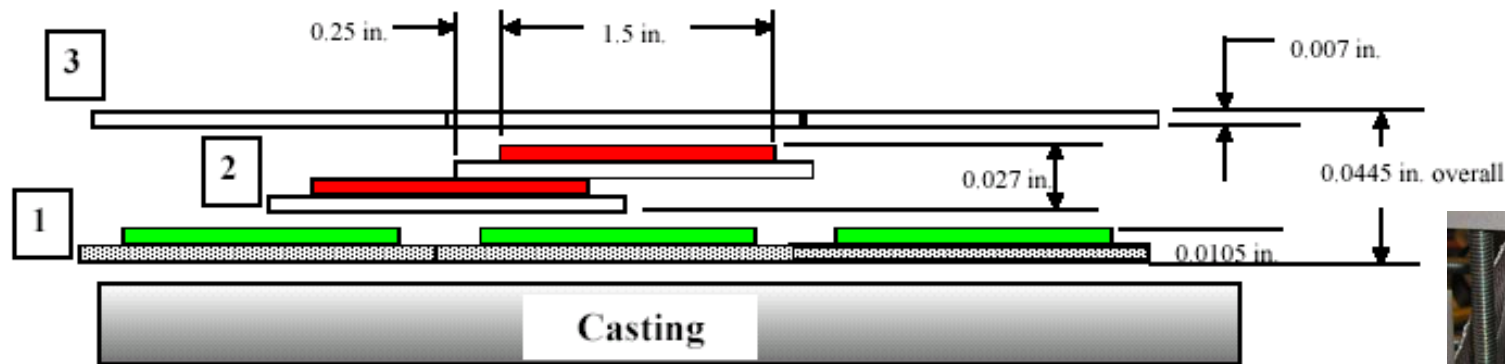
NCSX



- New insulation scheme, helps to minimize keystoneing
- Rolling or pre-forming of conductor is not a realistic option, due to the complex and changing geometry of the coils
- Smaller conductor helps to minimize Keystoneing
- *Between the conductor tolerance ± 0.008 in. and dimensional variations due to keystoneing, 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 “Romer” arm plus specially designed tools
 - Shim as required to maintain tolerance control

Ground Wrap Insulation Scheme

NCSX

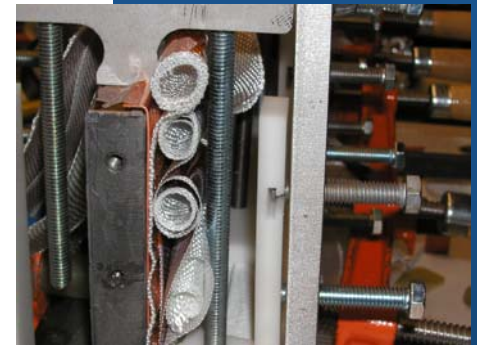


3 (1) Butt lapped layer
0.007 in. thick S-2 glass [2 inch nom. wide]

2 (1) Half-lapped layer of composite:
- 0.007 in. thick glass [2 inch nom. wide] & 0.0065(HN) Kapton [1.5 nom. wide] with adhesive
- X 2 = 0.027 in. thick

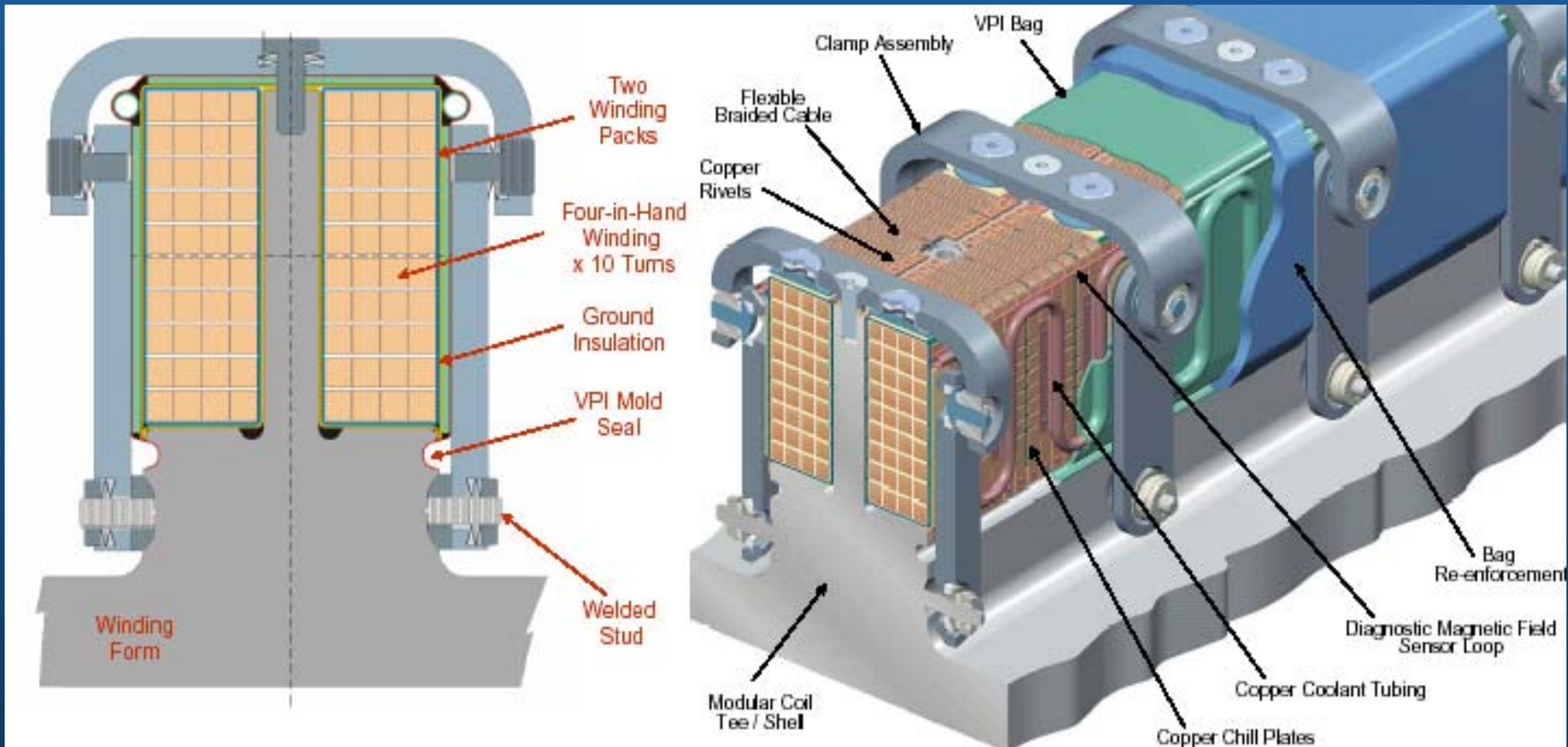
1 (1) Butt lapped layer of composite:
- 0.007 in. thick glass [2 inch nom. wide] and 0.0035 (HN) Kapton [1.5 nom. wide]) with adhesive

Tracking distance = 1.0 inches



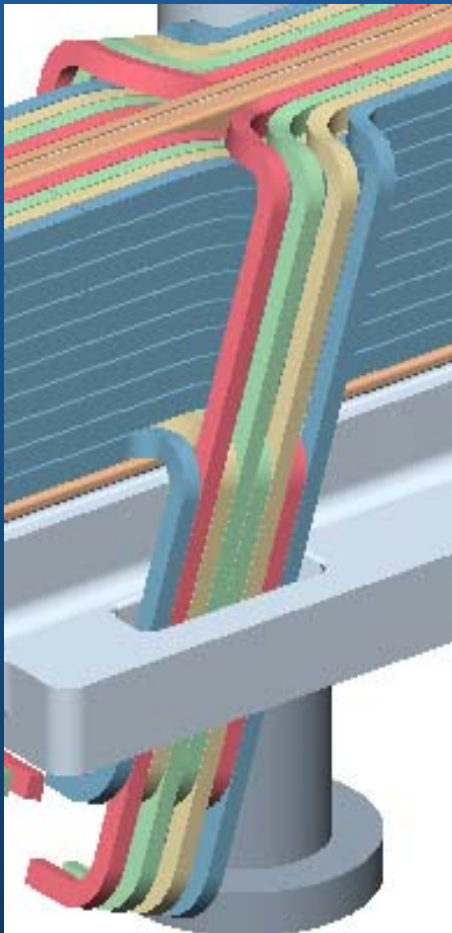
Modular Coil Winding Pack Assembly

NCSX

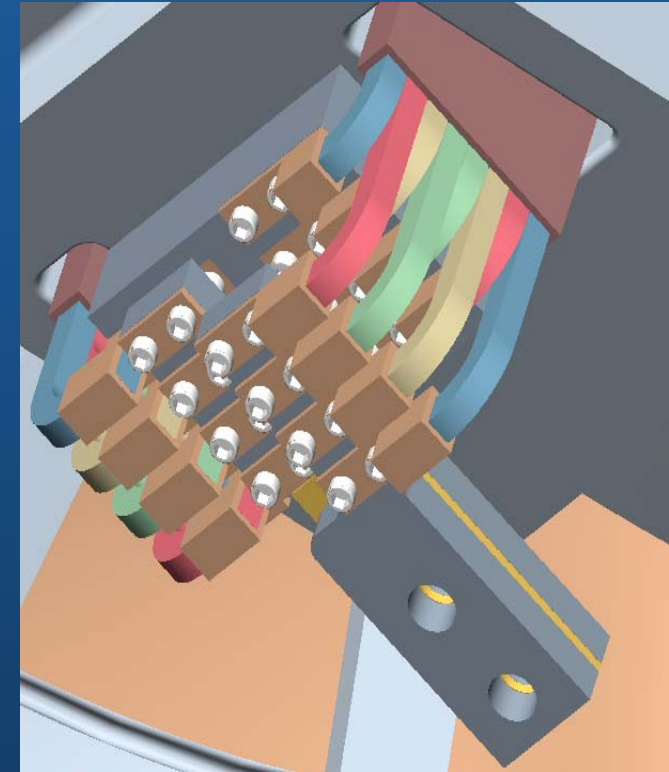


Modular Coil Manufacturing

NCSX

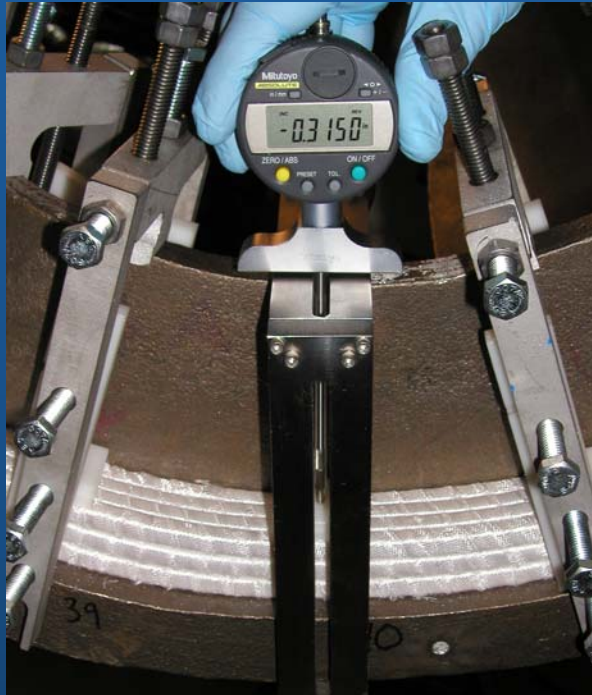


- Compacted copper conductor will arrive pre-insulated.
- Coil layers will be wound 4 conductors in-hand
- The upper and lower leads will join together and run along the side of the coil bundle and through the casting
- Leads will be terminated outside the casting [**First demonstrated on “Twisted racetrack coil”**]
- Details of the bracing for the conductors in this region will be an area of focus

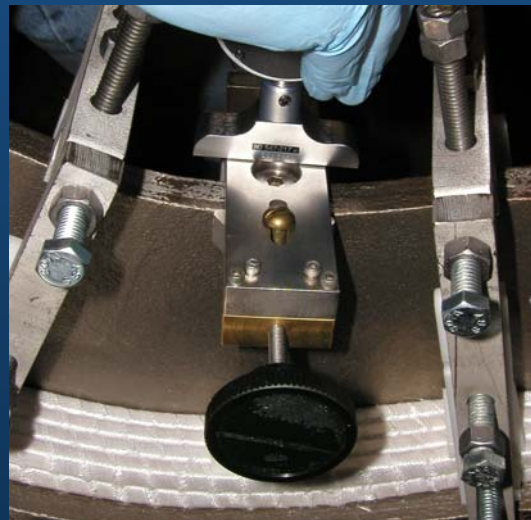


Coil Winding Metrology

NCSX



- Initial measurements are made using “Romer” Arm
- Use mechanical measurement fixture/gauge as conductor is being laid in position
 - Fixture fastens to top leg of MC casting using pre-tapped holes
 - Digital gauge measures from fixture to conductor surface [surface block will be used on conductors]
- Add or remove glass shims as necessary
- Periodically remeasure overall height using “Romer” arm



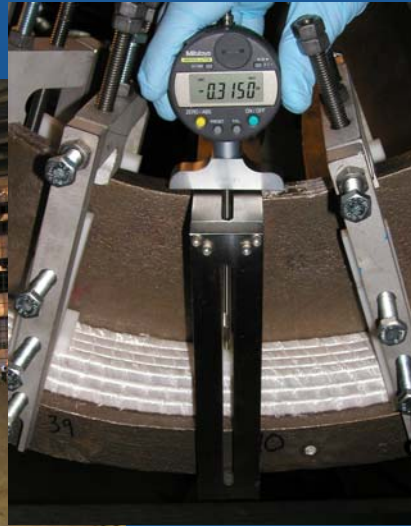
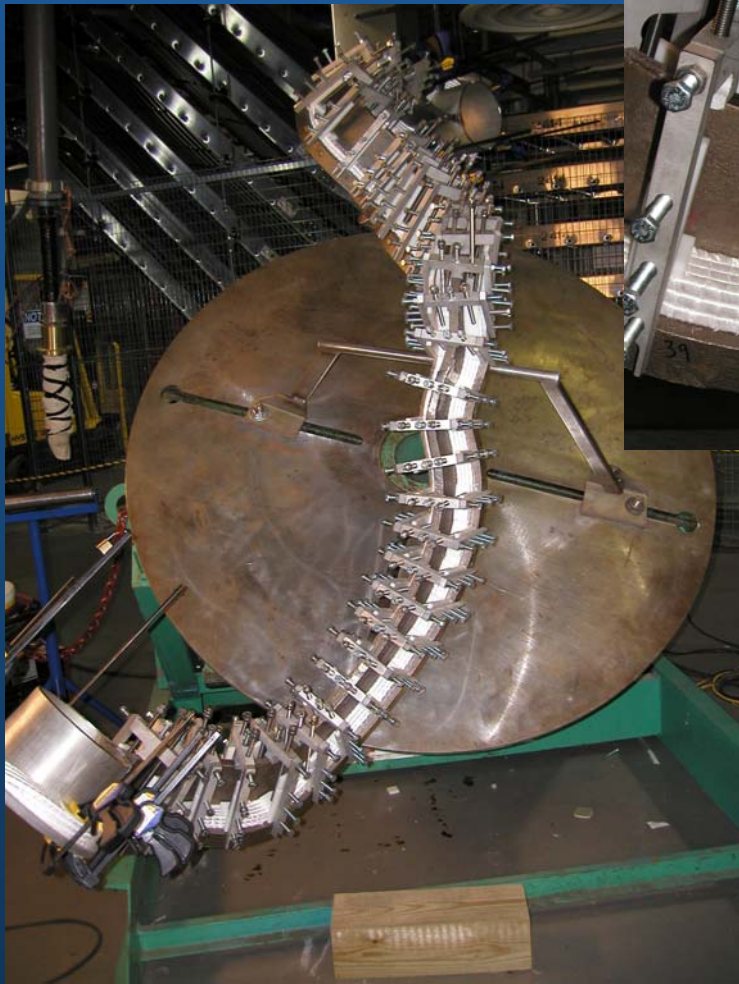
May 19-20, 2004

Final Design Review

J.H. Chrzanowski - 11

Inch Worm- Winding Trials

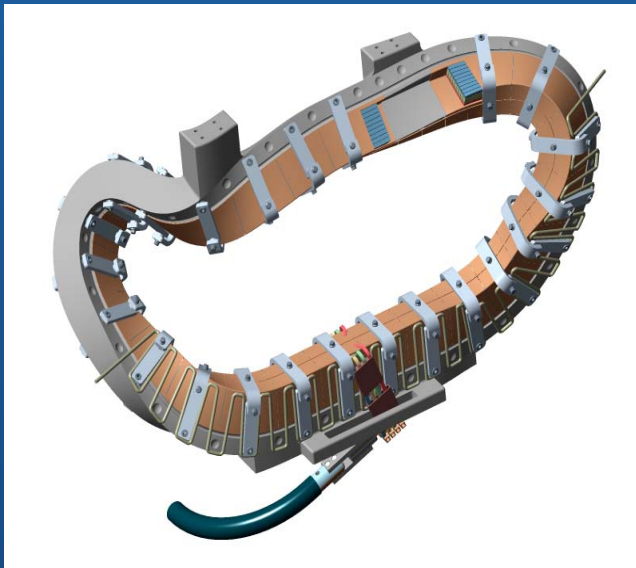
NCSX



- **The “Inch Worm” casting was used to:**
 - Develop winding techniques/procedures
 - Develop metrology instruments
 - Train winding crew in handling cable conductor

Twisted Racetrack Shaped Coil

NCSX



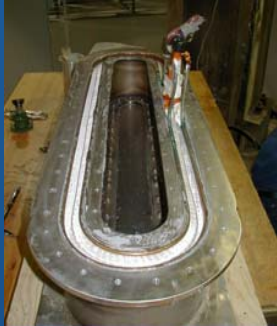
- **Twisted coil will capture many physical features of the NCSX Modular coils including:**
 - Mod coil Cross-section and Transitions
 - Conductor and Insulation scheme
 - Lead arrangement
 - Cooling arrangement (Chill plates)
- **Coil will be instrumented with strain gauges and thermocouples to monitor 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
 - First use of Autoclave
 - Verify thermal performance of the coil



Anticipated start mid July

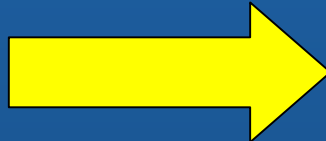
Evolution of R&D Winding / VPI Development

NCSX



Univ. of Tenn. Coil

First use of CTD-101K epoxy system for VPI



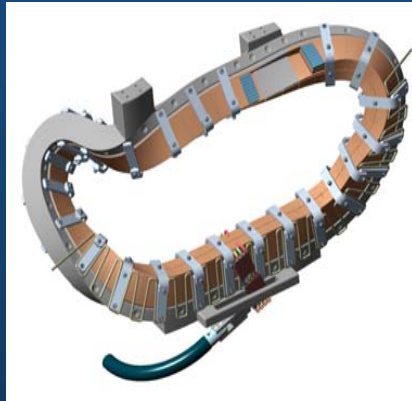
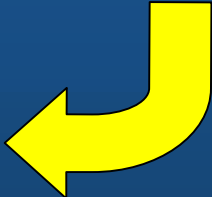
Straight Tee Section

First use of "Bag Mold" for VPI



Racetrack Coil

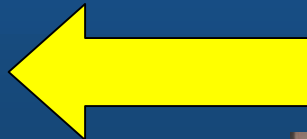
First winding experience & use of copper cladding



Twisted Racetrack

-Final coil lead configuration
-First use of autoclave for VPI

July 04



Full Scale Prototype Coil

First use of manufacturing processes

September 04



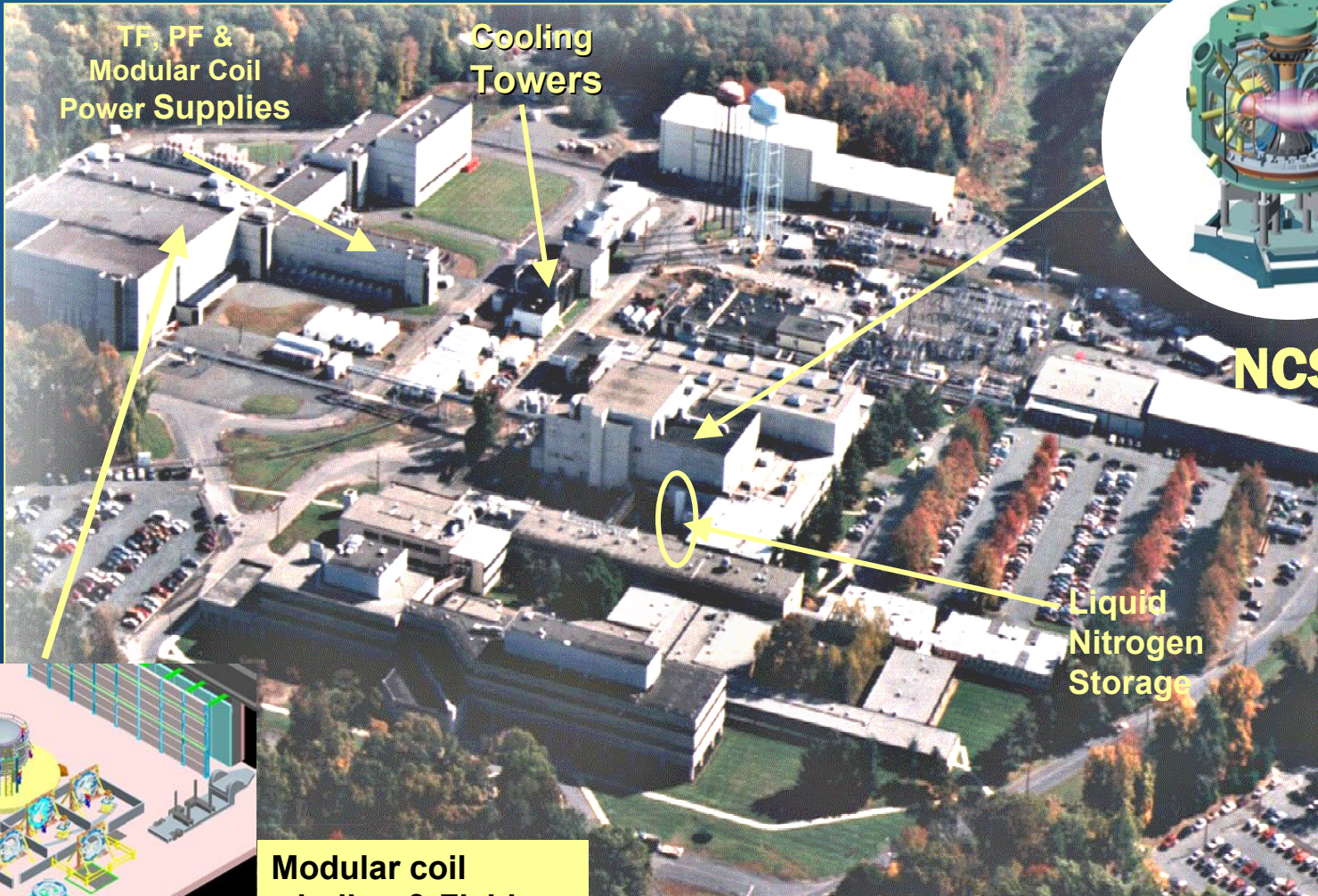
Inch-Worm Winding

-First use of shimming to control tolerance
-First use of 4 in hand conductor

Spring 04

Modular Coil Fabrication

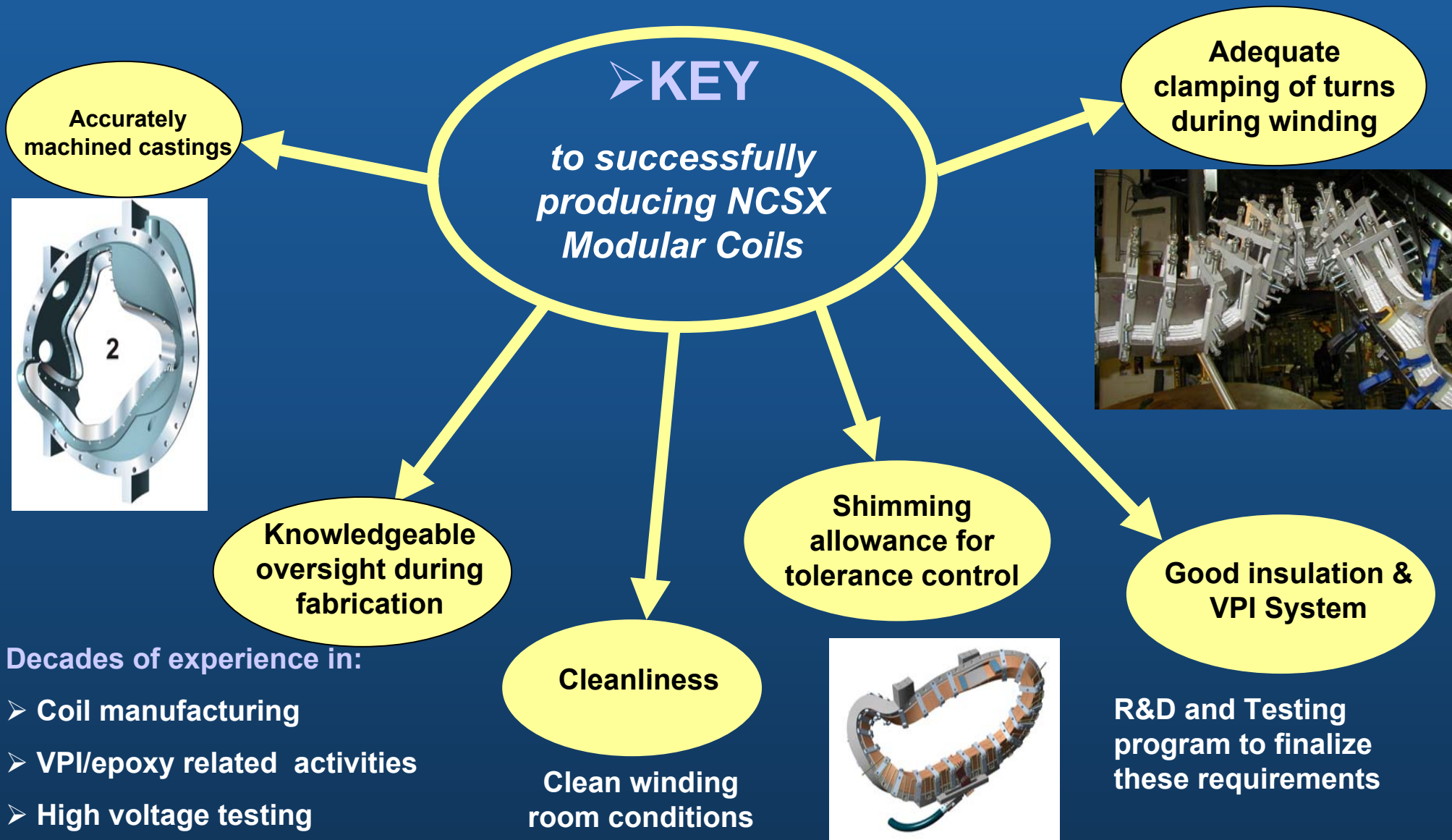
NCSX



Modular coil winding & Field Period assy. area

Modular Coil Success

NCSX



Modular Coil Winding Facility Operations Plan

NCSX

NCSX

Modular Coil Winding Facility Operations Plan

NCSX-PLAN-WFOP-00

April 1, 2004

Author: _____
James H. Chrzanowski- Coil Facility Manager

Reviewed By: _____
Steve Raftopoulos- Field Supervisor

Reviewed By: _____
Tom Meighan- Field Supervisor

Reviewed By: _____
Judy Malsbury- NCSX QA Representative

Reviewed By: _____
Jerry Levine- PPPL Safety Representative

Reviewed By: _____
Bill Slavin- PPPL IH Representative

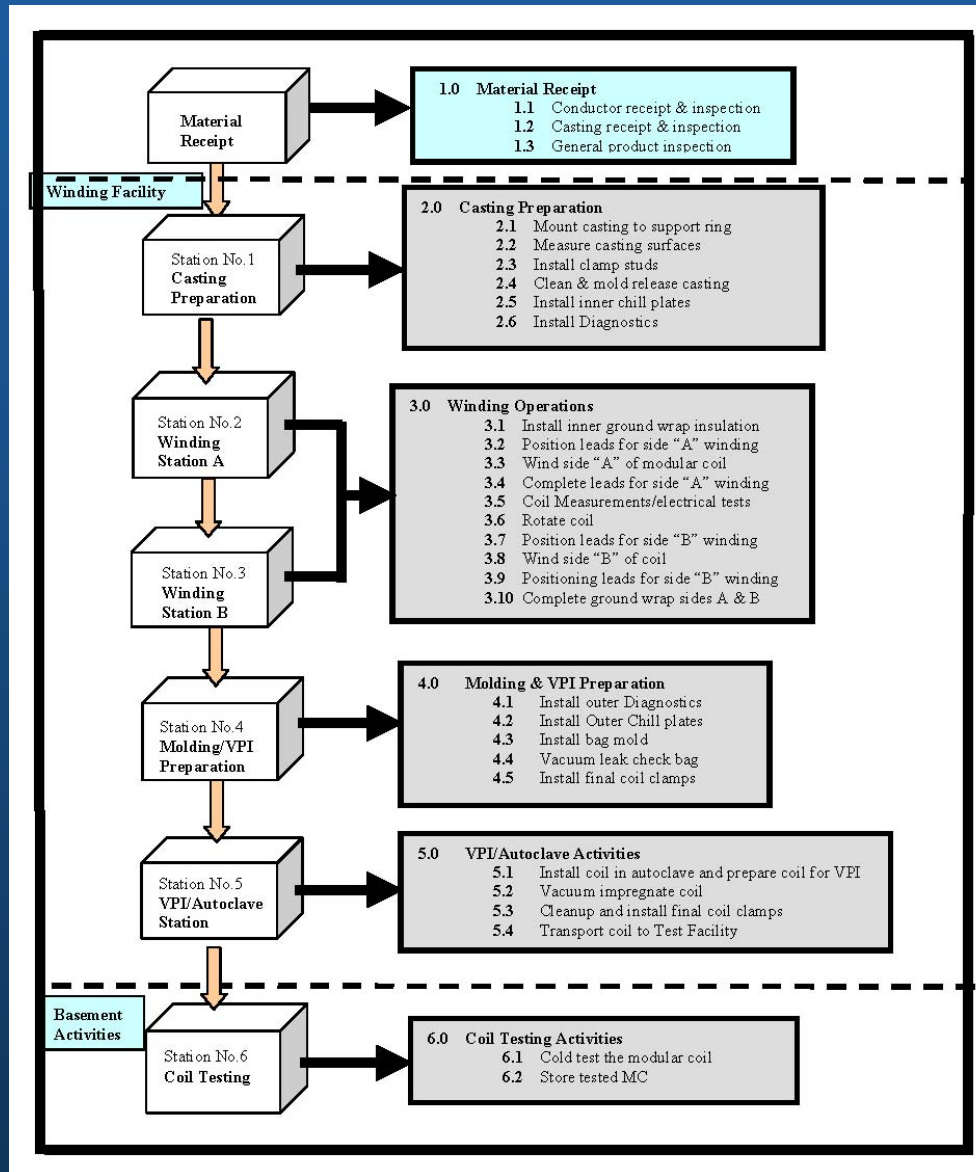
Approved By: _____
Larry Dudek- RLM for Coil Facility

1

- A Modular Coil Winding Facility Operations Plan has been written and approved.
- This document describes how the MCWF will function during the coil manufacturing
 - Workstations
 - Responsibilities
 - Safety and Training
 - Operating Guidelines
 - Communication
 - Documentation
 - Quality Assurance

Modular Coil Manufacturing Flow Plan

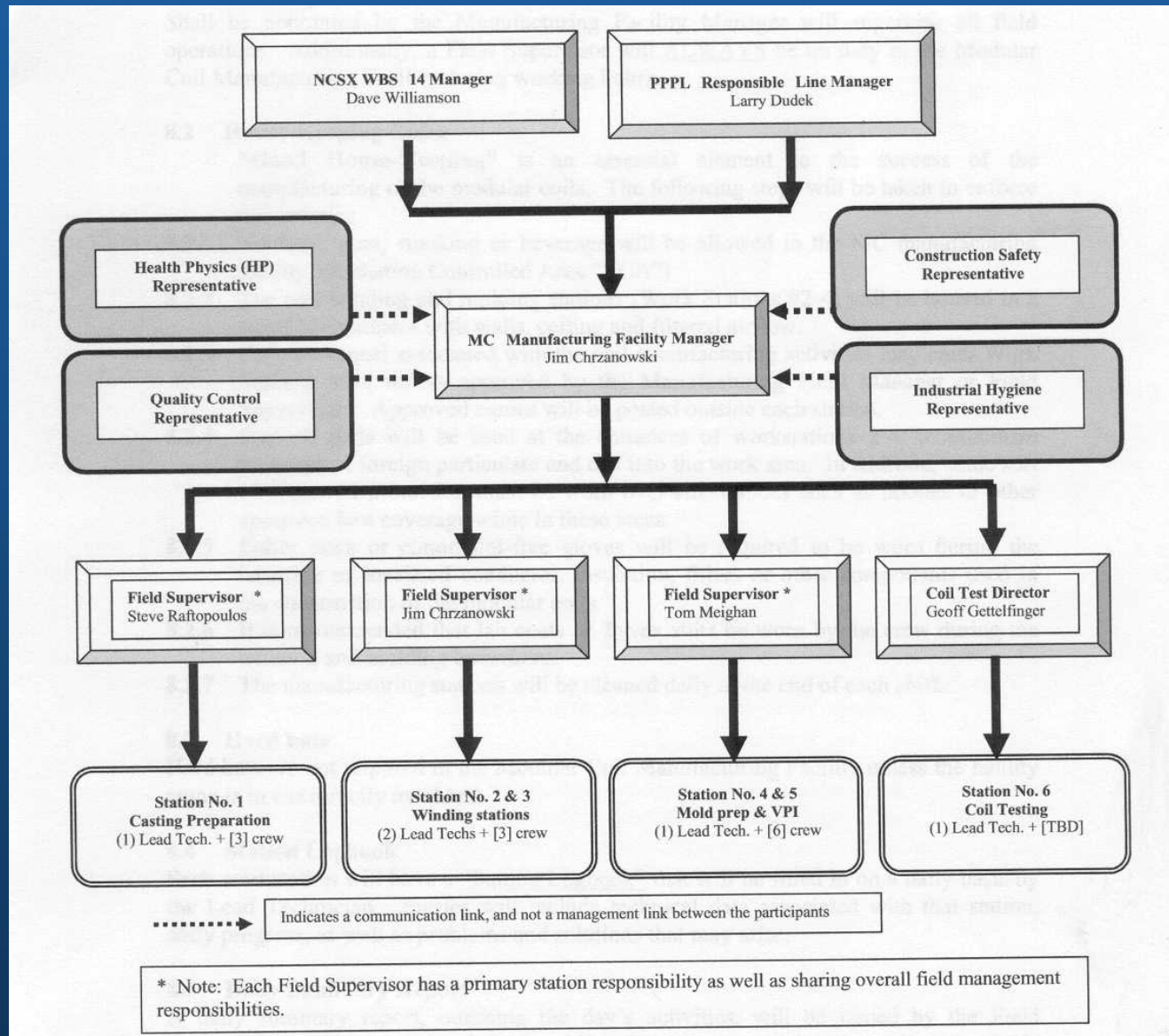
NCSX



- Flow plan outlines work stations and manufacturing steps
- Receipt of casting thru final testing

MCWF Organizational Chart

NCSX



Modular Coil MIT Plan

NCSX

NCSX

Modular Coil Manufacturing, Inspection, Test and Quality Assurance Plan

NCSX-MIT/QA-142-01-00

April 27, 2004

Author: _____ Date: _____
James H. Chrzanowski- Modular Coil Facility Manager

Reviewed By: _____ Date: _____
Judy Malsbury- NCSX QA Representative

Reviewed By: _____ Date: _____
Jerry Levine- PPPL Safety Representative

Reviewed By: _____ Date: _____
Dave Williamson- WBS Manager for Modular Coils
(WBS14)

Reviewed By: _____ Date: _____
Brad Nelson- Project Engineer for Stellerator Systems
(WBS 1) Manager

Approved By: _____ Date: _____
Larry Dudek- RLM for Modular Coil Mfg. Facility

Controlled Document

THIS IS AN UNCONTROLLED DOCUMENT ONCE PRINTED.
Check the NCSX Engineering Web prior to use to assure that this document is current.

- MIT Plan has been written and reviewed.
- Document will be used during the manufacturing of the Twisted Racetrack Coil, modified and approved for the production coils
- The MIT in conjunction with procedures will dictate the manufacturing process

Manufacturing Documents

NCSX

- **NCSX-PLAN-WFOP-00** [MC Winding Facility Operations Plan]
- **NCSX-MIT/QA-142-01-00** [MC MIT/QA Plan]
- **Manufacturing Procedures**
 - **NCSX-PROC-MCF-001** [MC Material Receipt]
 - **NCSX-PROC-MCF-002** [MC Station 1- Casting Preparation]
 - **NCSX-PROC-MCF-003** [MC Station 2&3- Winding]
 - **NCSX-PROC-MCF-004** [MC Station 4- Mold Preparation]
 - **NCSX-PROC-MCF-005** [VPI and Final Operations]
 - **D-NCSX-OP-G-159** [MC Test Facility Operation]

Modular Coil Fabrication

NCSX

- The Modular Coil Winding Facility will be located in the D-site Test Cell [formerly occupied by TFTR]
- Six manufacturing stations
 - Station 1- Casting Prep
 - Station 2 & 3- Winding stations
 - Station 4- Mold preparation
 - Station 5- VPI and post VPI
 - Station 6- Cryo test (Located in basement)
- The coils will **vacuum-pressure-impregnated** (VPI) in an autoclave
- Maintain coil current center tolerance of **+/- 0.020 inches** by shimming between turns and layers

Modular Coil Manufacturing Facility

NCSX



MCWF Clean Rooms

NCSX

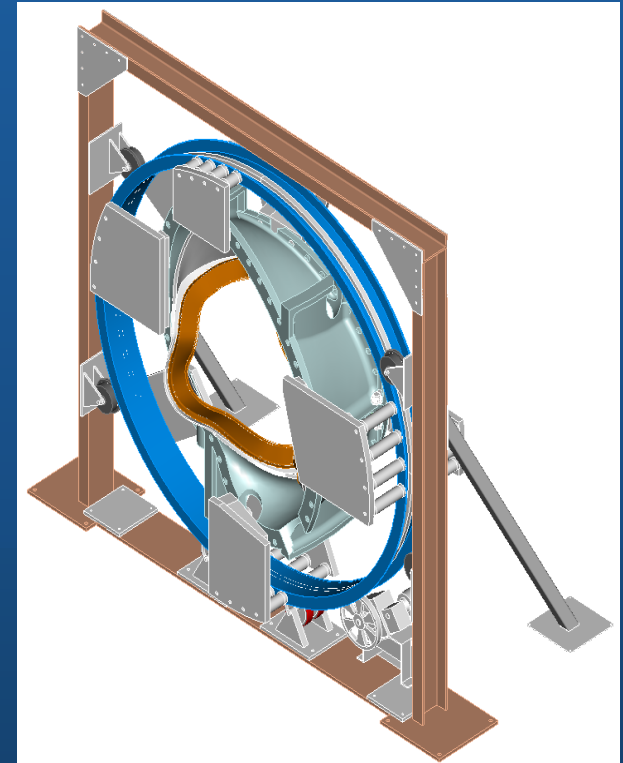


- The winding and mold stations will be located in enclosed rooms where **cleanliness** can be controlled.
- Three clean rooms are being constructed.
- Modular coils will be positioned in the rooms via a sliding roof panel.
- External vacuum system for cleaning purposes, as well as filtered room ventilation



Coil Turning Fixtures

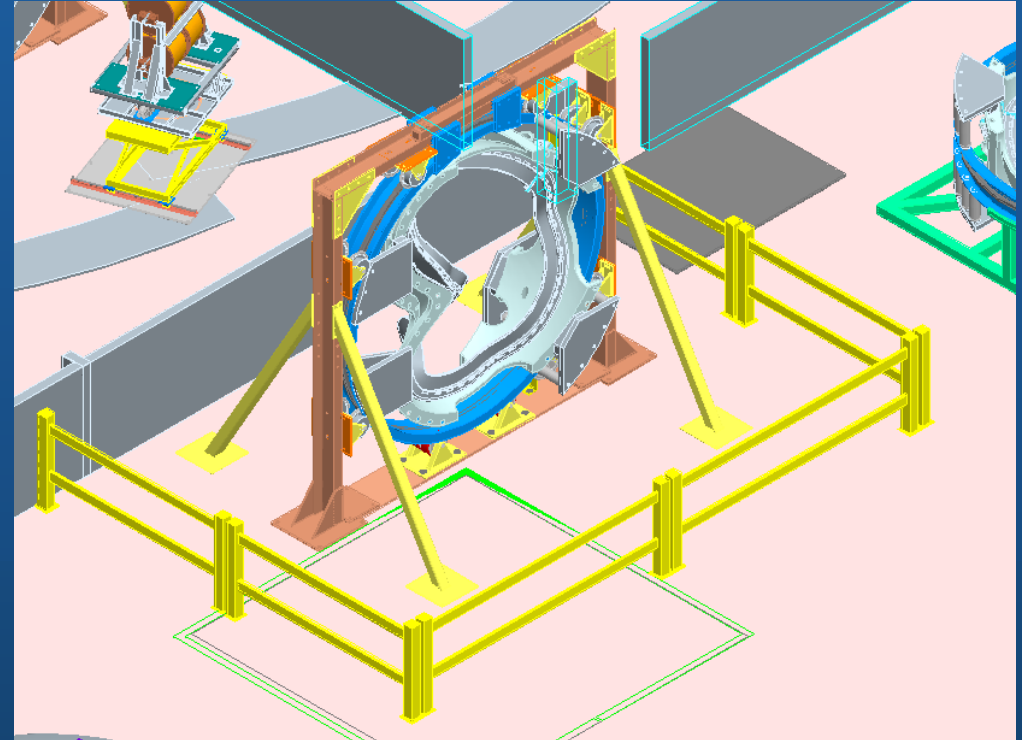
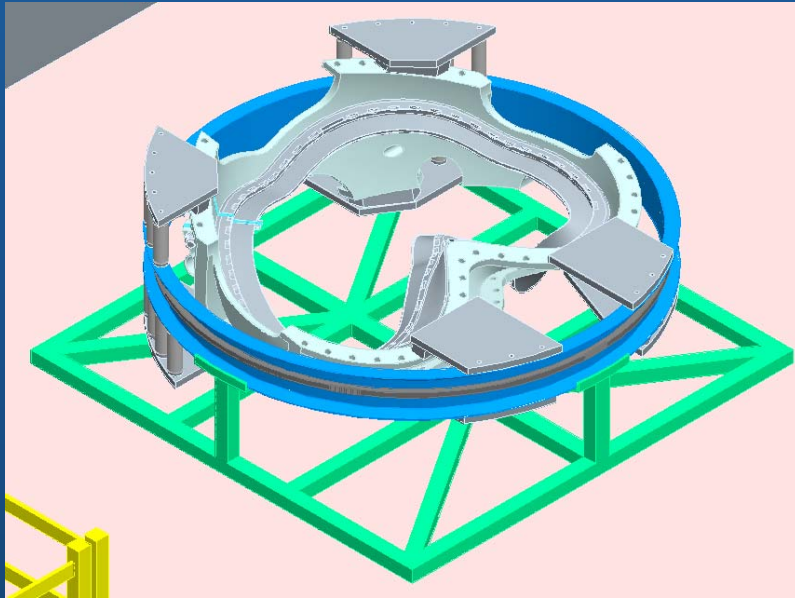
NCSX



- Vertical turning fixtures will accommodate (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

NCSX



Casting Preparation

- Mount casting to support ring
- Measure/inspect casting surfaces
- Install coil clamp studs
- Clean & mold release winding surfaces
- Install inner chill plates & measure

Procedure No. NCSX-PROC-MCF-002

12 working days per coil

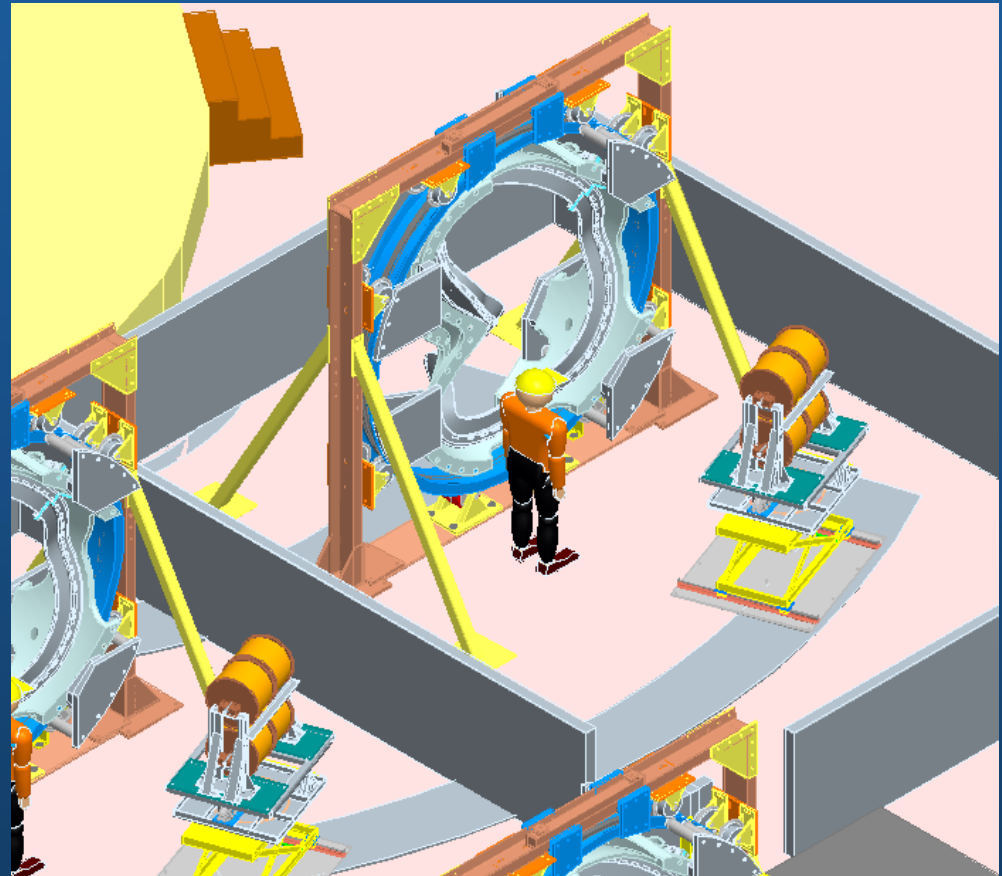
Coil Winding Station #2 & 3

NCSX

Winding Operations [2 stations]

- Install inner ground wrap insulation
- Position leads for side “A” winding
- Wind side “A” of modular coil
- Measure turns as wound
- Complete leads for side “A” winding
- Reposition coil in turning fixture
- Position leads for side “B” winding
- Wind side “B” of coil
- Measure turns as wound
- Complete leads for side “B” winding
- Complete ground wrap sides A & B

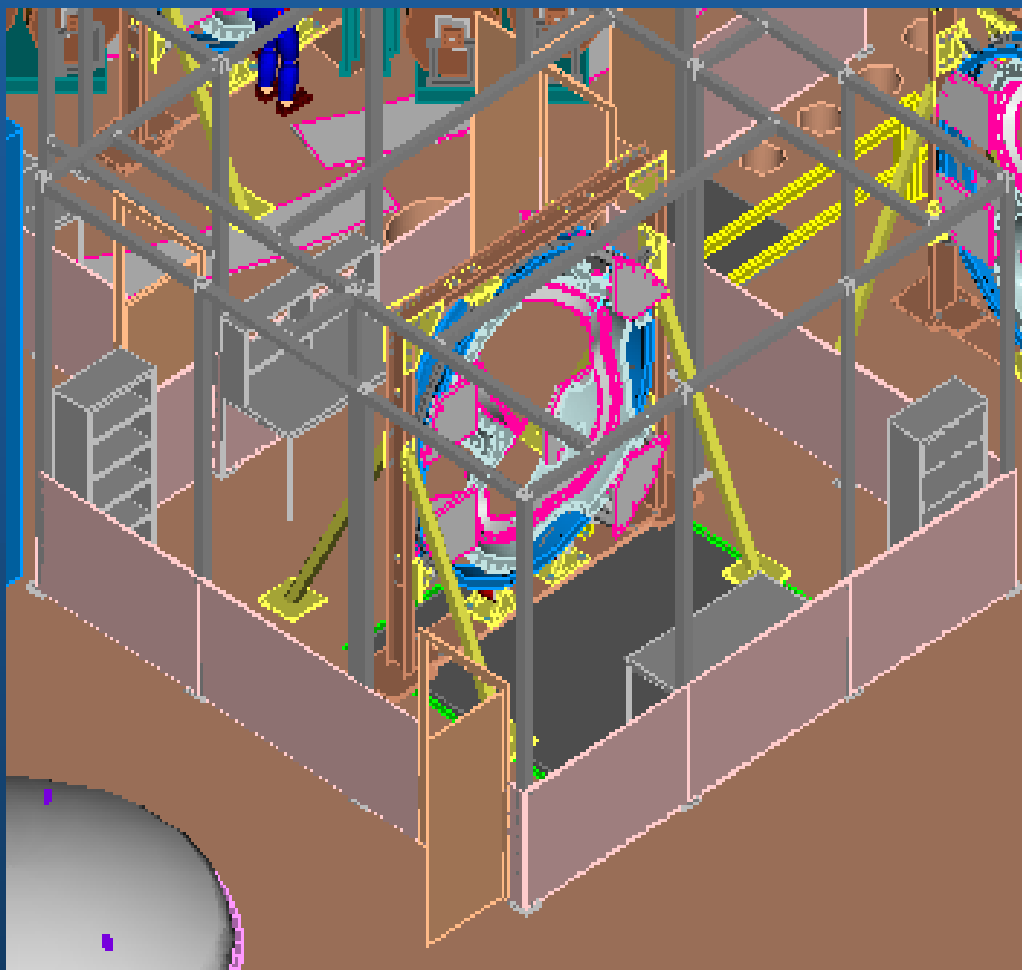
Procedure No. NCSX-PROC-MCF-003



38 working days per coil

Molding/VPI Preparation Station #4

NCSX



Molding & VPI Preparation

- Install outer Diagnostics & measure
- Install Outer Chill plates
- Install bag mold
- Vacuum leak check bag mold
- Install coil molding clamps

Procedure No. NCSX-PROC-MCF-004

15 to 25 working days per coil

VPI Station #5

NCSX



VPI/Autoclave Activities

- Install coil in autoclave and prep for VPI
- Vacuum impregnate coil
- Cleanup and install final coil clamps
- Transport coil to test facility

VPI- (12) working days per coil

Post VPI- (5) working days per coil

Cold Testing- (5) working days per coil

Procedure No. NCSX-PROC-MCF-005

Autoclave Installation

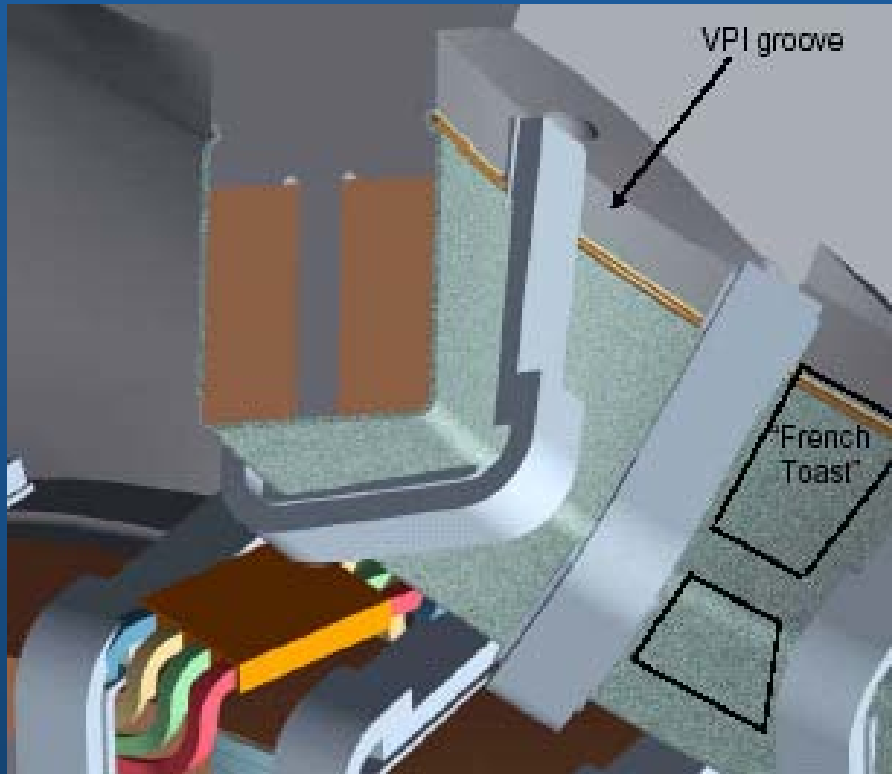
NCSX



- Autoclave being transported to coil winding facility

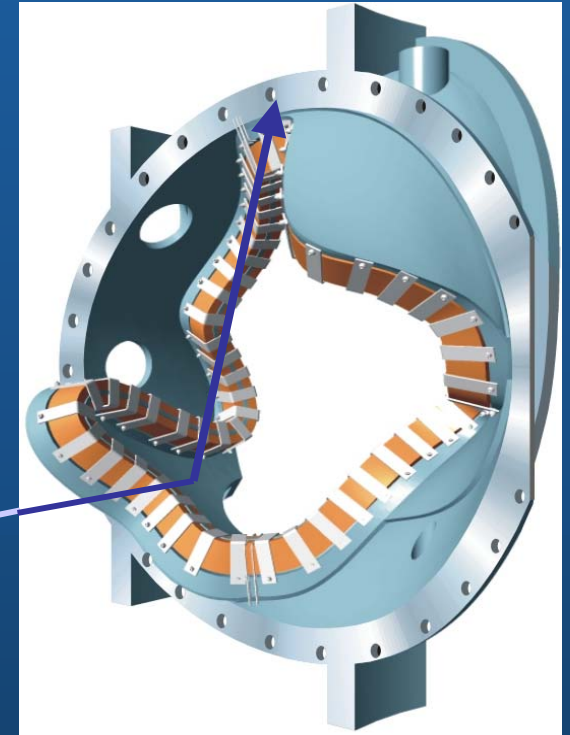
Vacuum-Pressure Impregnation (VPI)

NCSX



-Modular coils will be VPI'd in vertical position

-Epoxy bleed holes are provided at the highest point of casting to minimize risk of voids during VPI process

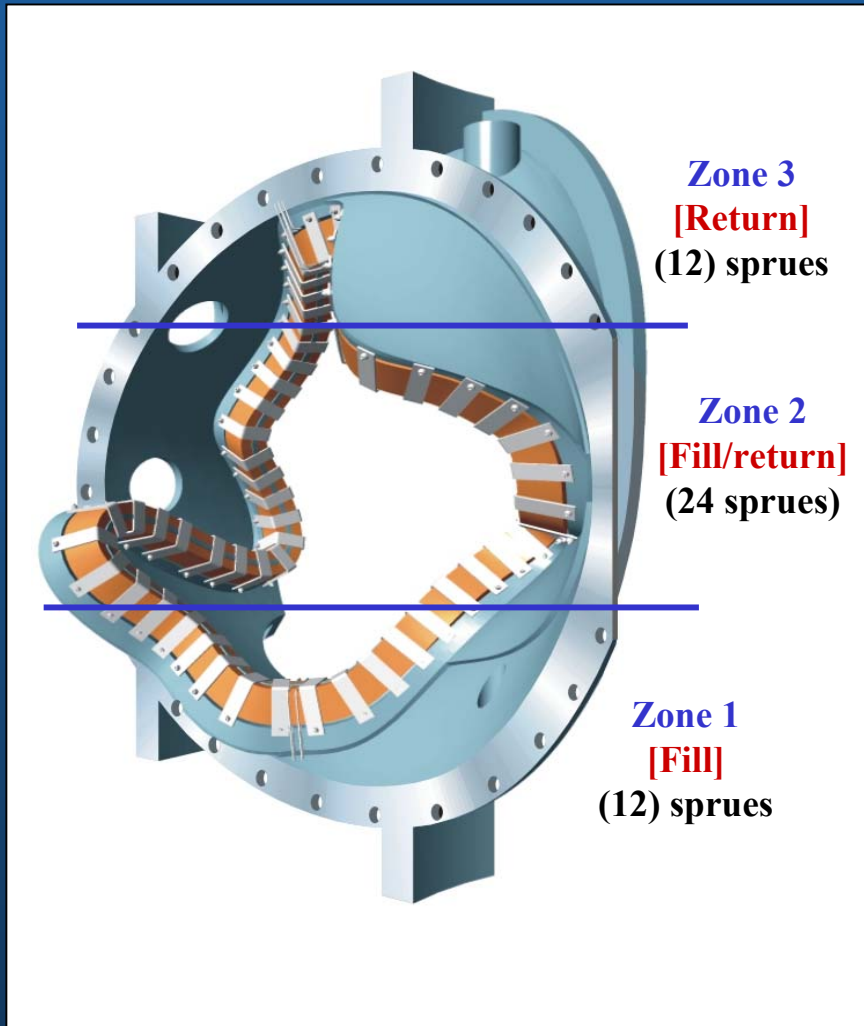


-“Bag Mold” -silicone rubber tape (vacuum seal) and epoxy filled felt (side wall stiffness) is placed over the ground wrap/ chill plates.

-“VPI Grooves”-silicone bag is secured with copper tubing pressed into machined grooves located on the casting.

Vacuum-Pressure Impregnation (VPI)

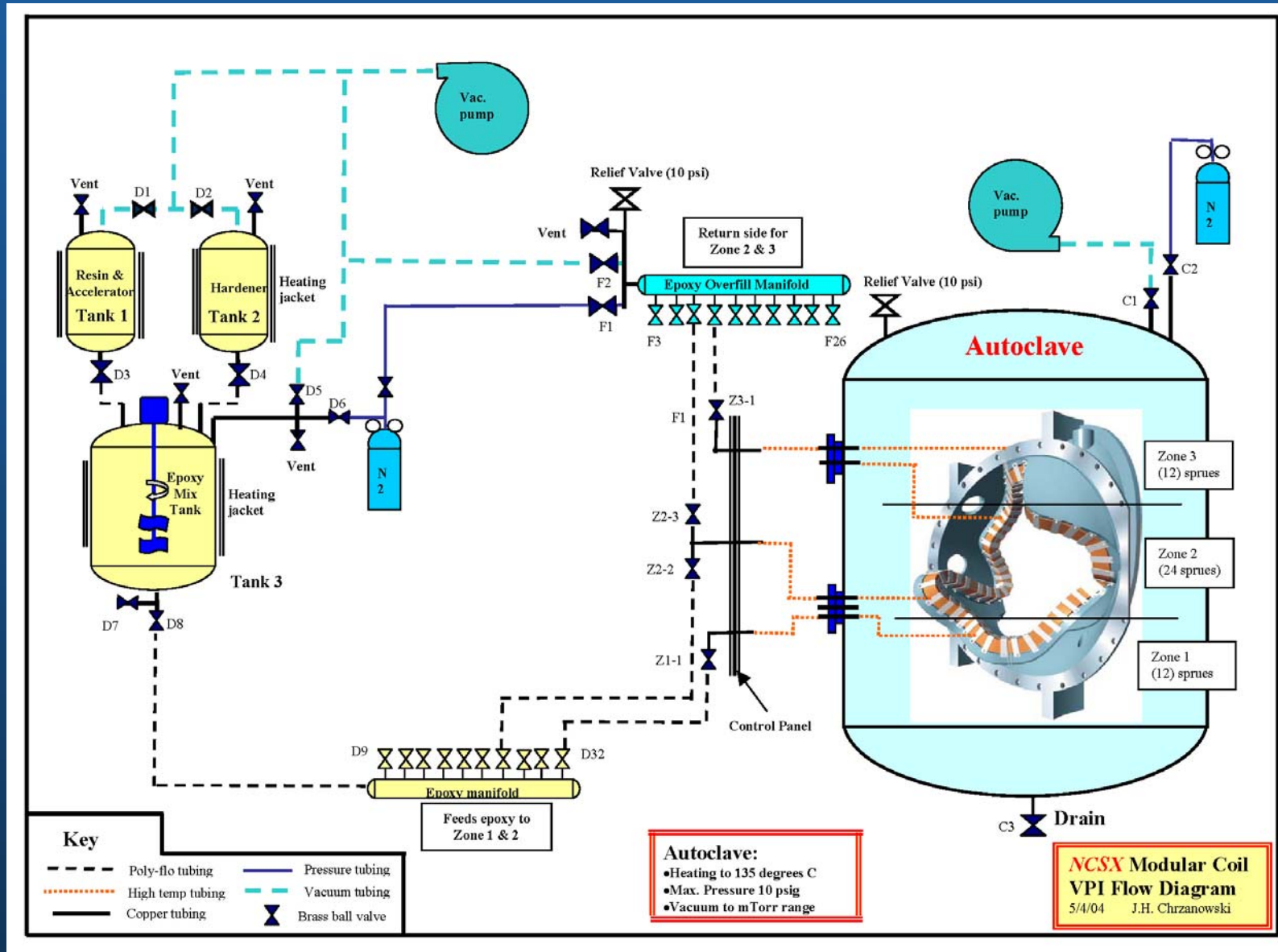
NCSX



- During the VPI process, the Modular Coil will be divided into 3 zones
 - Zone 1- supply only
 - Zone 2- supply and return
 - Zone 3- return only
- The autoclave will initially be maintained at vacuum matching the vacuum inside of the “bag mold” [minimize potential leaks]
- As the coil reaches the ½ fill mark, the autoclave atmosphere will slowly shift from vacuum to pressure (5 psig max) to support the bag mold
- Once filled, autoclave will return to atmospheric pressure prior to beginning the ramp up of temperature to cure the epoxy

Modular Coil VPI Flow Diagram

NCSX

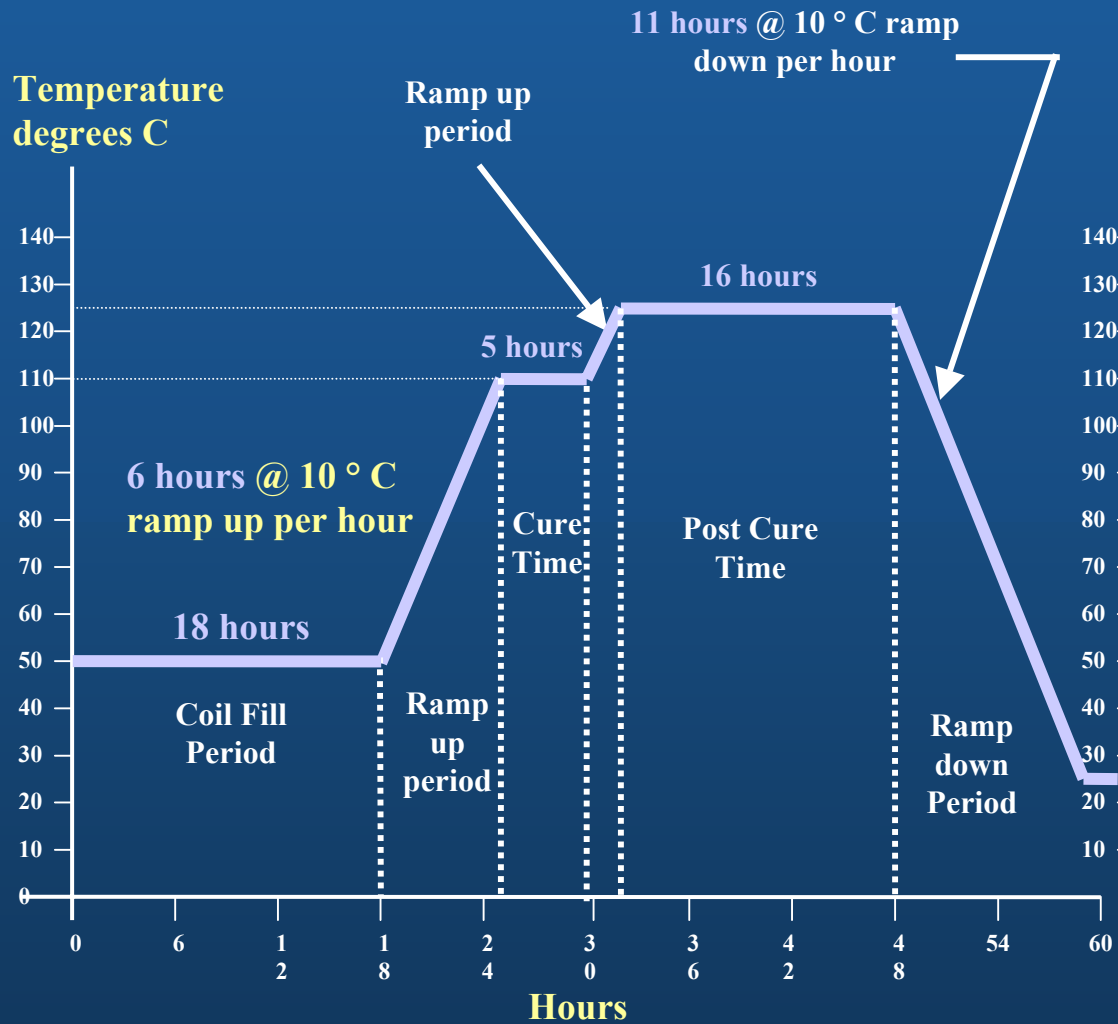


NCSX MODULAR COIL VPI CYCLE

NCSX



Epoxy component mixing



Viscosity measurements



"Scrambled Egg" test to verify Gel temperature

Modular Coil Manufacturing Schedule

NCSX



Summary- Completions

NCSX

- 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:
 - Determined the mechanical and thermal properties of the epoxy impregnated conductor
 - “Keystone test” have helped to define the conductor size, tolerance control and manufacturing processes
 - Developed and demonstrated a sound “VPI” plan (“Bag Mold” and epoxy delivery method)
 - Developed an Winding Facility Operations Plan and MIT
 - Manufacturing procedures are being written
 - Experience gained in winding Racetrack shaped coil and “Inch Worm” have helped to define the manufacturing plan

Summary- R&D and Manufacturing Preparations

NCSX

- **Remaining R&D/ Manufacturing Activities Include:**
 - Complete remaining epoxy/conductor mechanical/thermal tests
 - Complete cooling method R&D activities
 - Wind “Twisted” Racetrack Coil
 - Complete fabrication of tooling and setup of Modular coil manufacturing facility
 - Complete Modular coil manufacturing procedures
 - Perform trial winding operations on “Prototype” Modular coil
- *Good progress is being made in developing the detailed methods required to produce modular coils which meet their technical requirements within cost and schedule.*