NCSX Peer Review
Mold & VPI Process for Modular Coils

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Mold & VPI Process

- Agenda
  - Objective of Mold & VPI Program
  - VPI Terminology
  - Issues Associated with VPI Process
  - Proposed Modular Coil Mold Assembly
  - Description of VPI System
  - Description of VPI Process

Objective of Mold & VPI Program

- Design and demonstrate a vacuum tight mold system for VPI of Modular Coils

- Develop a detail process for VPI of the Modular Coils
  - Epoxy selection
  - Equipment/system identification
  - Detail process plan

VPI Terminology

- VPI- Vacuum Pressure Impregnation
- Sprues- Fittings for epoxy entrance & exit from coil mold
- Bag Molding- A less expensive method of building a mold where high tolerance outside dimensions are not required and can accommodate more difficult configurations. Can be made using silicone sheet or tape with a rigid strong back for support
- Milking- Term used for back flowing epoxy through coil once coil has been filled to remove trapped gas pockets
- Pot life *(working time)*- The life of the epoxy from the time that it is mixed until it begins to gel

VPI Terminology-continued

- Soak Period: Period of time following epoxy fill in which additional epoxy may be wicked into the coil insulation usually under slight positive pressure
- Gel Point: The time at which the viscosity of the epoxy mixture rises and the mixture begins to solidify
- Ramp up- Process of raising the temperature to cure a coil during VPI
- Cure temperature: Temperature at which the epoxy begins to solidify and to reach cured properties
- Post-Cure Temperature: Temperature at time which maximum mechanical and electrical properties are reached
- Degass: To remove trapped air in epoxy components via 1-2 Torr vacuum

VPI Terminology-continued

- "Scramble Egg Test"- Test used to verify correct the mixture of components prior to introducing the epoxy to the coil.
- Viscometer: operates on the principle of rotating a cylinder or disc immersed in the liquid under test and measuring the torque necessary to overcome the viscous resistance to rotation. (digital readout)

Issues Associated with any VPI Process

- Epoxy selection and Characterization
  - *Right epoxy for the right situation*
  - Working time (Pot life)
  - Viscosity (How does epoxy viscosity change with temperature/ time?)
  - *Understand your epoxy*
- Epoxy mixing Process
  - Small unmixed pockets of accelerator can cause exothermic reaction & begin rapid cure within local pocket
- Degassing Issues
  - Boil off of even small quantities of accelerator can vary the curing of the epoxy

Issues Associated with any VPI Process-continued

- Delivery of epoxy to coil:
  - Most efficient way of getting epoxy into mold.
  - Correct quantity and location of Sprues is important
- Having the right equipment to complete the job
- Construction of the Mold
  - Unique shape/configuration of the Modular coils does not allow for conventional molding methods without high $$$$$
  - Unique shape can be a challenge in sealing the mold

Epoxy Selection

- **Plan is to use CTD-101K**
  - Product of *Composite Technology Dev. Inc.*
  - 3- Component epoxy system
  - Excellent performance at cryogenic temperatures with a long pot life and low viscosity

  - **Mix Ratio**
  - Resin (Part A) 100.0 parts by weight
  - Hardener (Part B) 90.0 parts by weight
  - Accelerator (Part C) 1.5 parts by weight

  - **Cure Cycle**
  - 5 hours @ 100 ° C (Cure)
  - 16 hours @ 125 ° C (Post cure)

Epoxy Selection

- **Pot Life:**
  - 145 hours @ 25° C……. 1300 Cp viscosity
  - 60 hours @ 40° C……. 400 Cp viscosity *
  - 20 hours @ 60° C……. 100 Cp viscosity

    (Values as noted by epoxy manufacturer)
  - * PPPL verified >50 hours @ 45° C
  - Epoxy from the first tensile specimen potted on December 10, 2002 (room temperature) remained uncured until January 7, 2003.

Epoxy properties will be tested by outside contractor per SOW NCSX-SOW-142-02-00 (out for review)

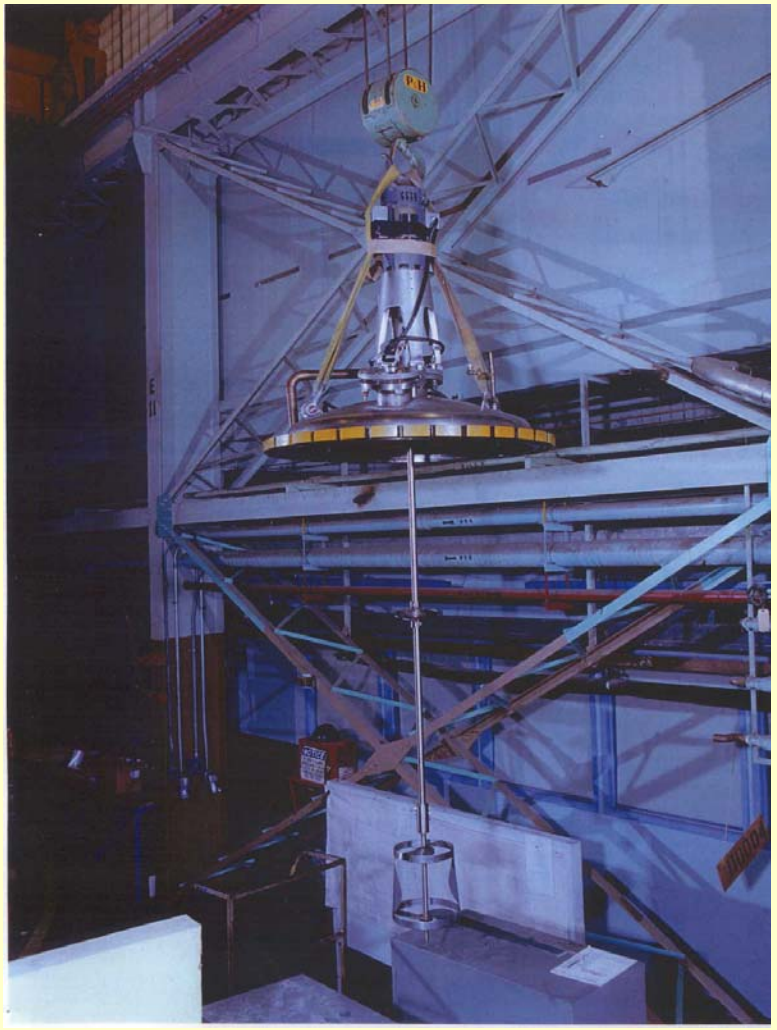
GOOD WORKING TIME!!!

Epoxy Viscosity Measurements

- It is necessary to fully understand the resin formula which is being used.
- A number of viscosity measurements will be made prior to the impregnation phase to characterize the resin system from the start of mix thru the "Gel" state.
- Viscosity measurements will be made using digital Viscometer.

Epoxy Mixing

- Even distribution of the accelerator is critical.
- Small unmixed pockets of accelerator can have an accelerated exothermic reaction and begin a very rapid cure within this local pocket
- A test will be performed to verify the performance of the mixing process using wall paper paste with the same viscosity as the epoxy formula. Two ounces of green food coloring will be added to determine the efficiency of the mixing propellers.



Degassing Issues

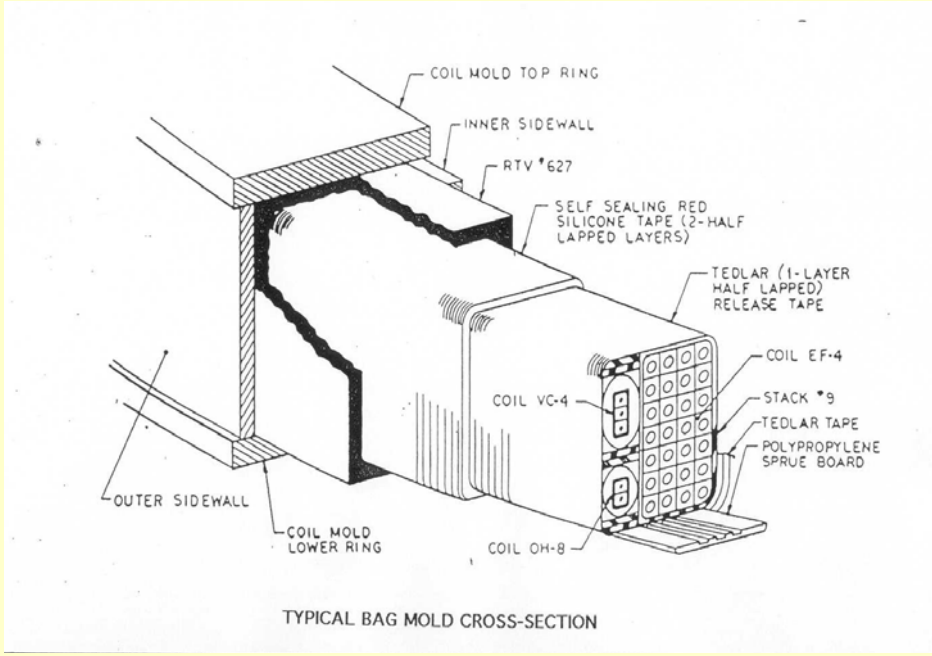
- Degassing of the resin during the mixing operation is another critical issue.

- A vacuum of 2 to 3 torr will be maintained on the epoxy mixture. This will allow degassing of the mixture, but will be above the vapor pressure of any of the components particularly the accelerator.

- It was determined from previous tests that the accelerator if boiled off even in small quantities could vary the curing of the epoxy.

Epoxy Entry & Distribution

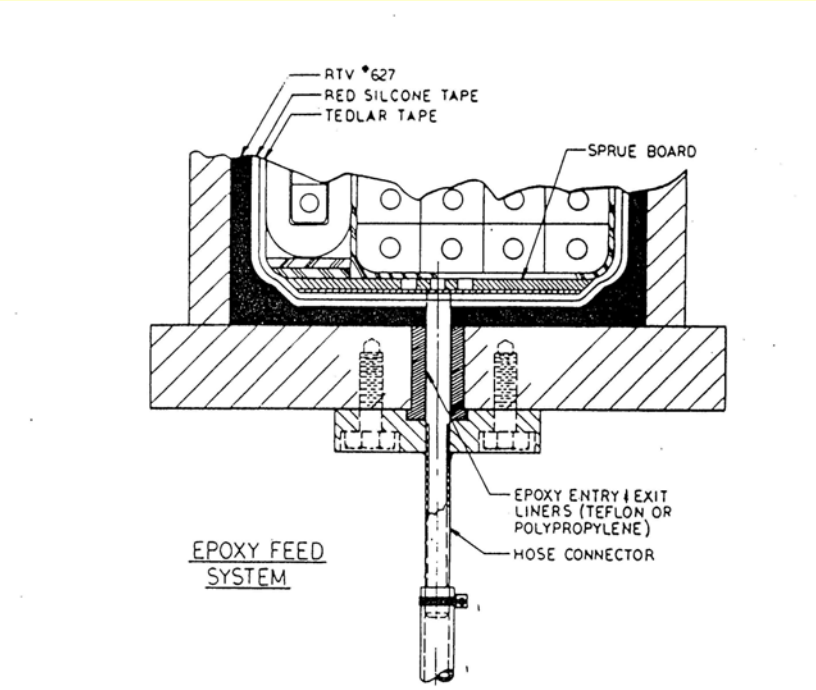
- The TFTR PF coils required the use of **Waffle boards** that were fabricated of polyethylene plate and had a series of concentric and cross tracks machined on the coil side of the plates.
  - Waffle boards were utilized after the 1st. attempt to cast stack 7B. The initial impregnation attempt had to be aborted because the resin could not properly flow from the sprues.



Typical TFTR PF coil

Epoxy Entry & Distribution

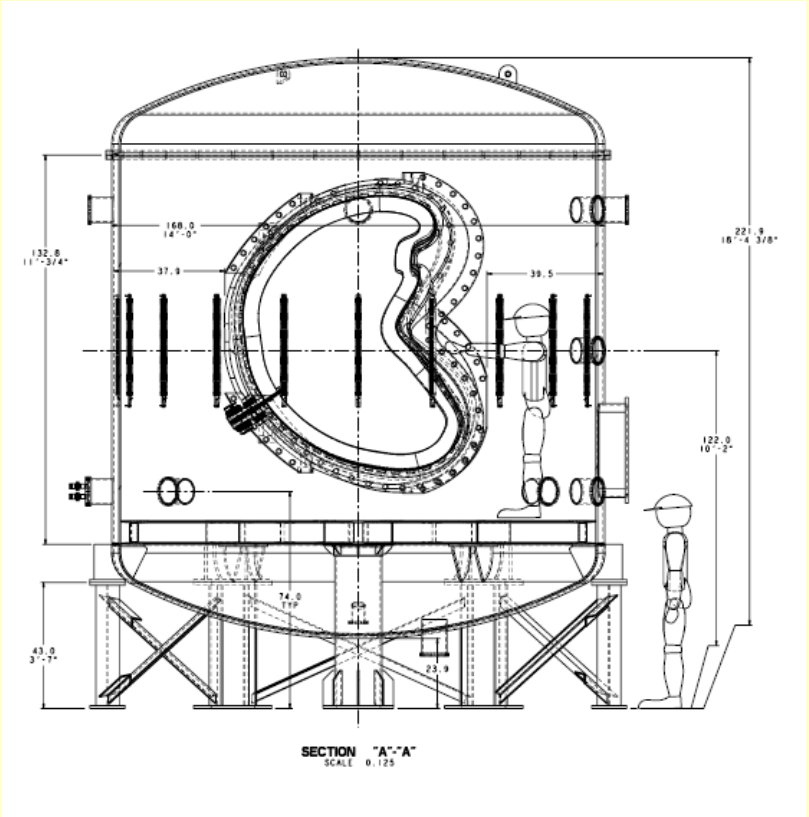
- For the TFTR PF coils the epoxy for was delivered thru entry ports "Sprues" on the bottom of the mold attached to the waffle boards. The grooves assured an adequate and fast distribution of resin throughout the bottom of the coil, minimizing the risk of dry spots.



SPRUE BOARD AND ENTRY PORTS

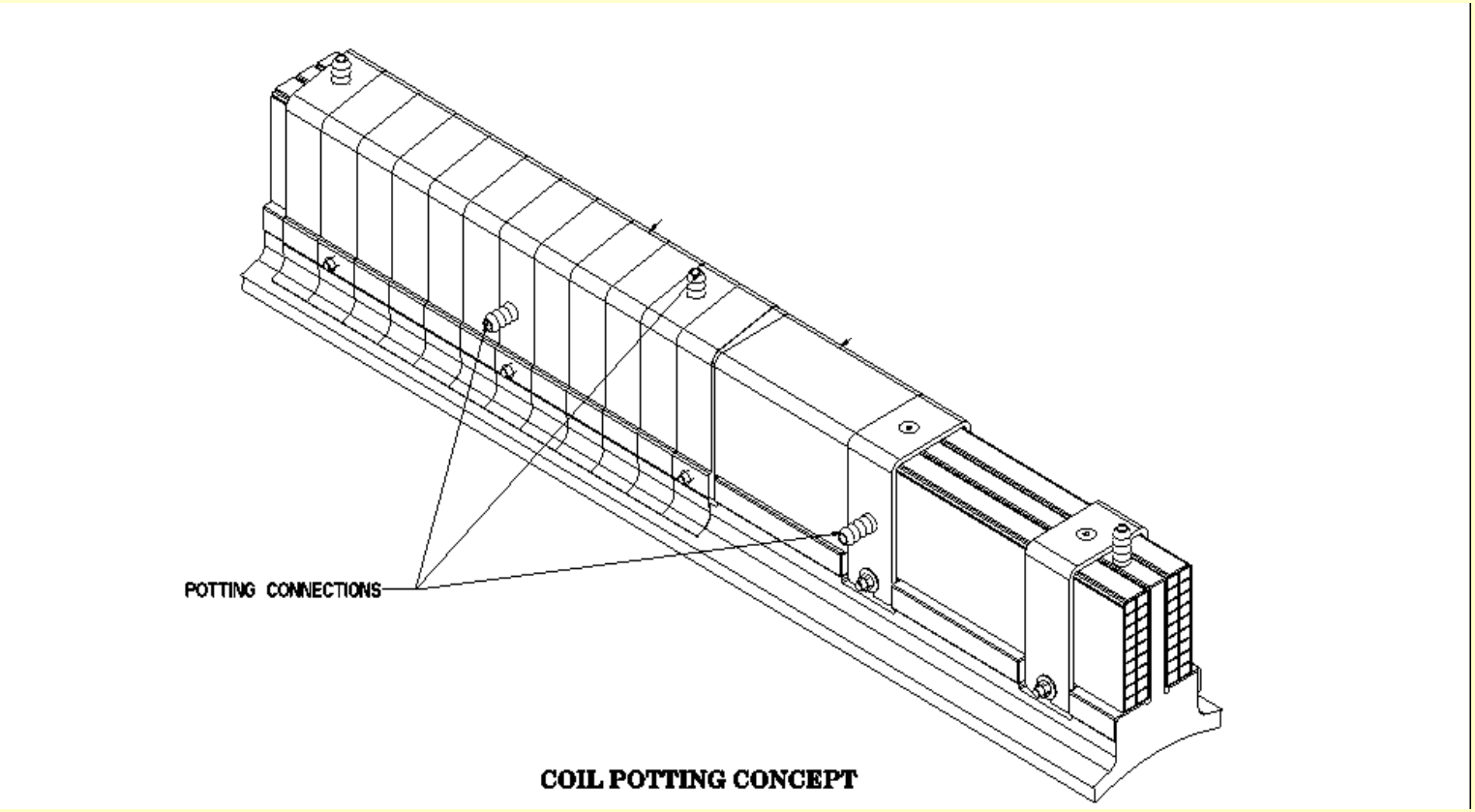
Epoxy Entry & Distribution

- Due to the unique configuration of the NCSX Modular Coils it is recommended that the coils be placed in the vertical position for epoxy impregnation
- Entrance points "Sprues" will be located approximately every 12 inches alternating their position
- 20 to 30 Sprues in total will be required per coil



Epoxy Entry & Distribution-continued

Modular coil Spru locations



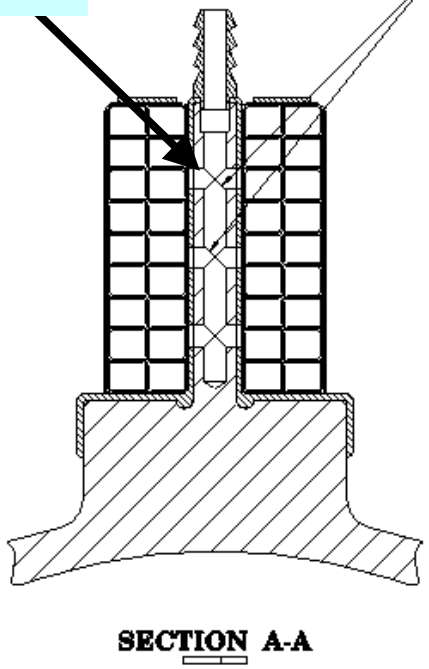
Epoxy Entry & Distribution-Sprues

Requires modifications to Coil casting & clamps

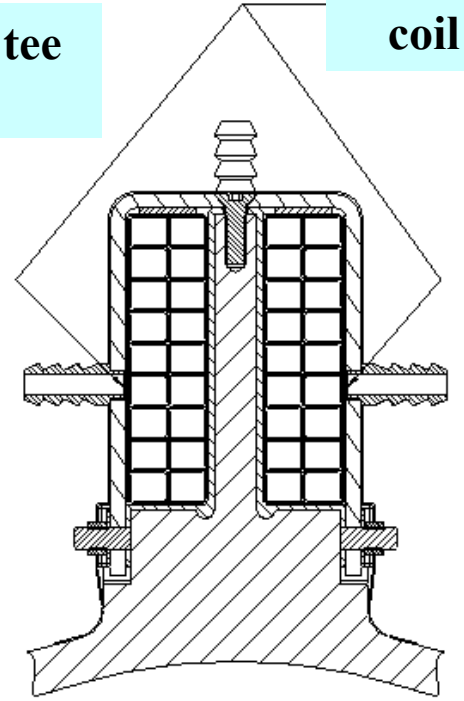
Occurs every 24 inches

Cross drill tee section

Add sprue's to coil clamps

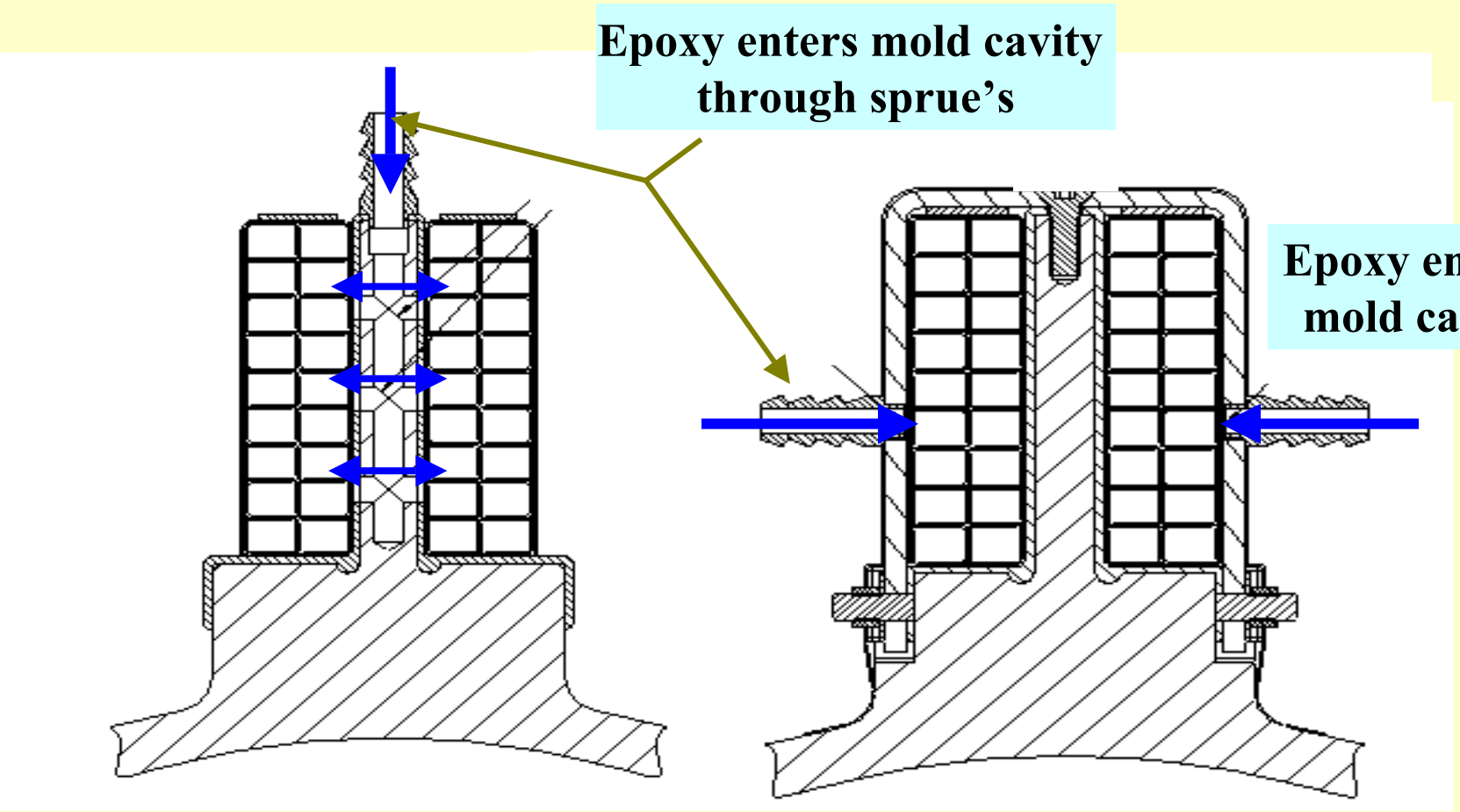


SECTION A-A

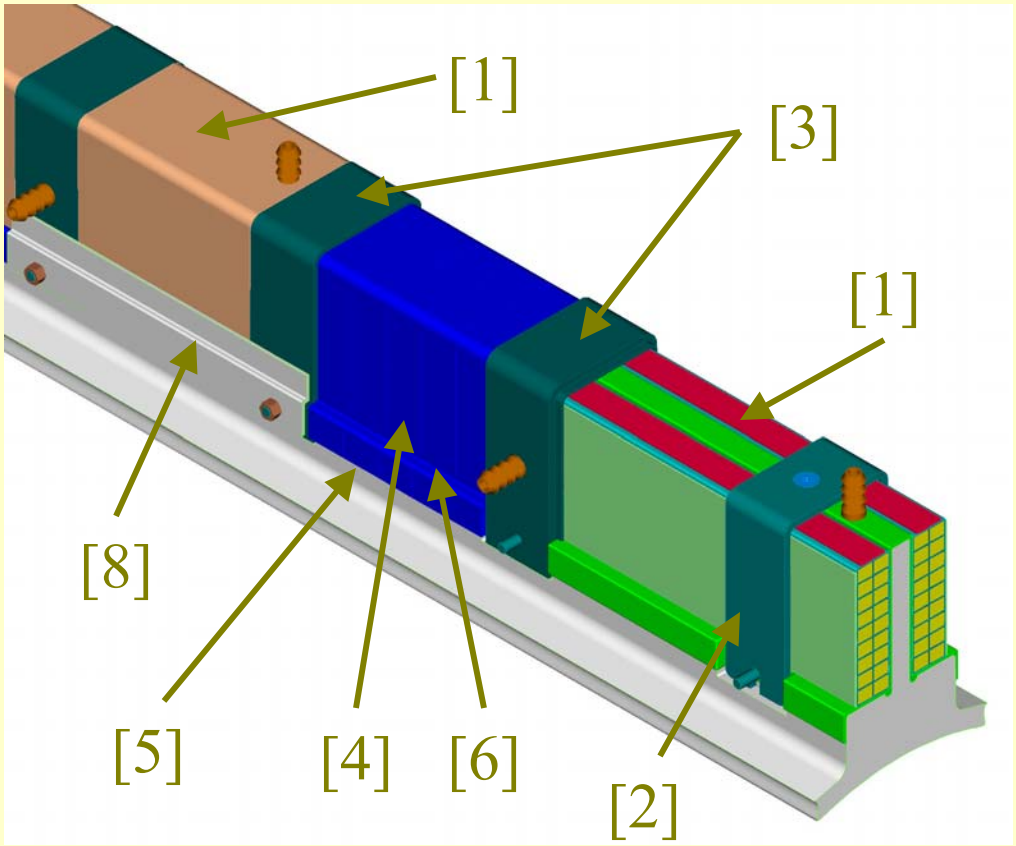


SECTION B-B

Epoxy Flow Into Modular Coil

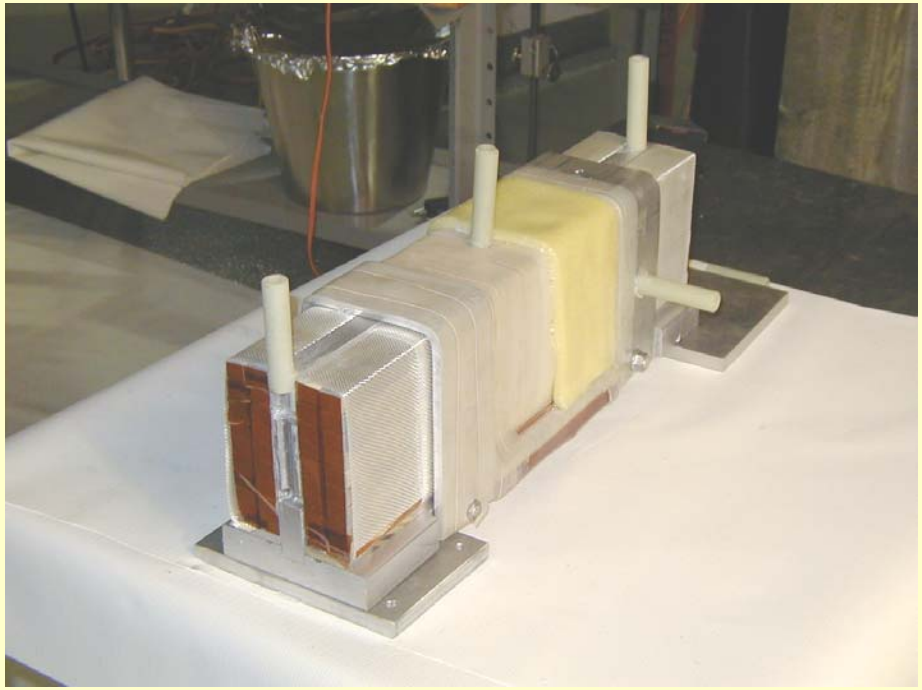


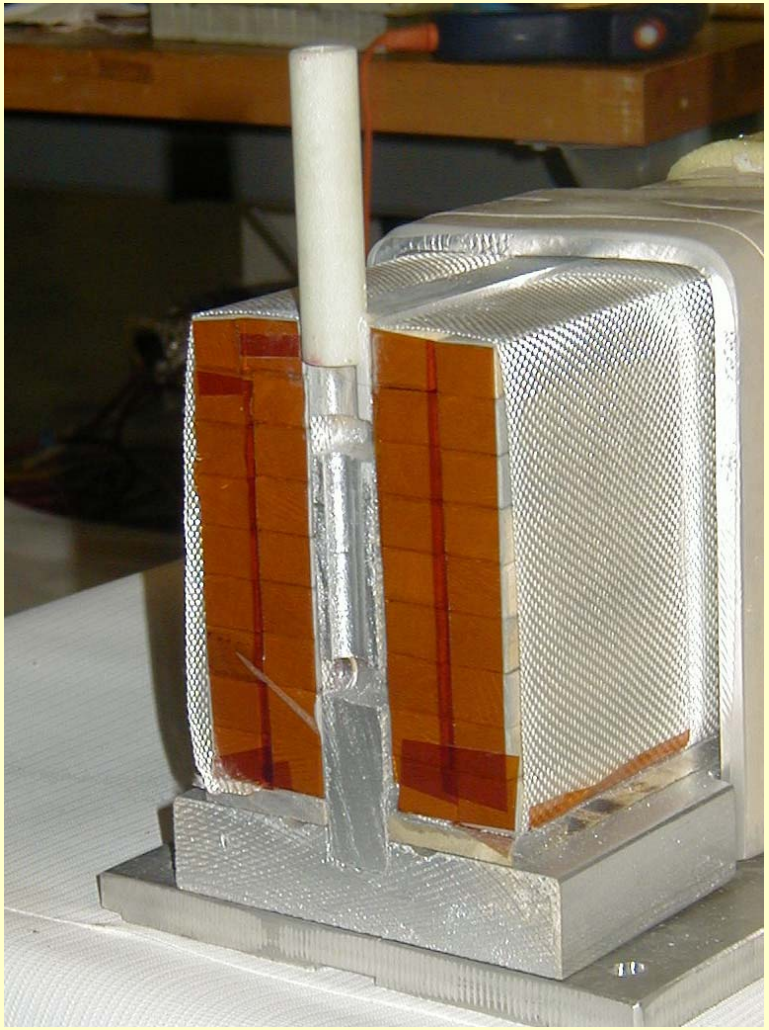
Proposed Modular Coil Mold Assembly



- Install coil ground wrap [1]
- Install final coil clamps [2]
- Install Silicone boots over clamps [3]
- Install (2) Layers silicone rubber tape mold [4]
- Seal ends of molds with silicone RTV [5]
- Paint mold with 2-part RTV 627 (several layers) [6]
- Install epoxy impregnated felt between the clamps [7]
- Install strong backs between clamps [8]

Model of Modular Coil Mold Assembly



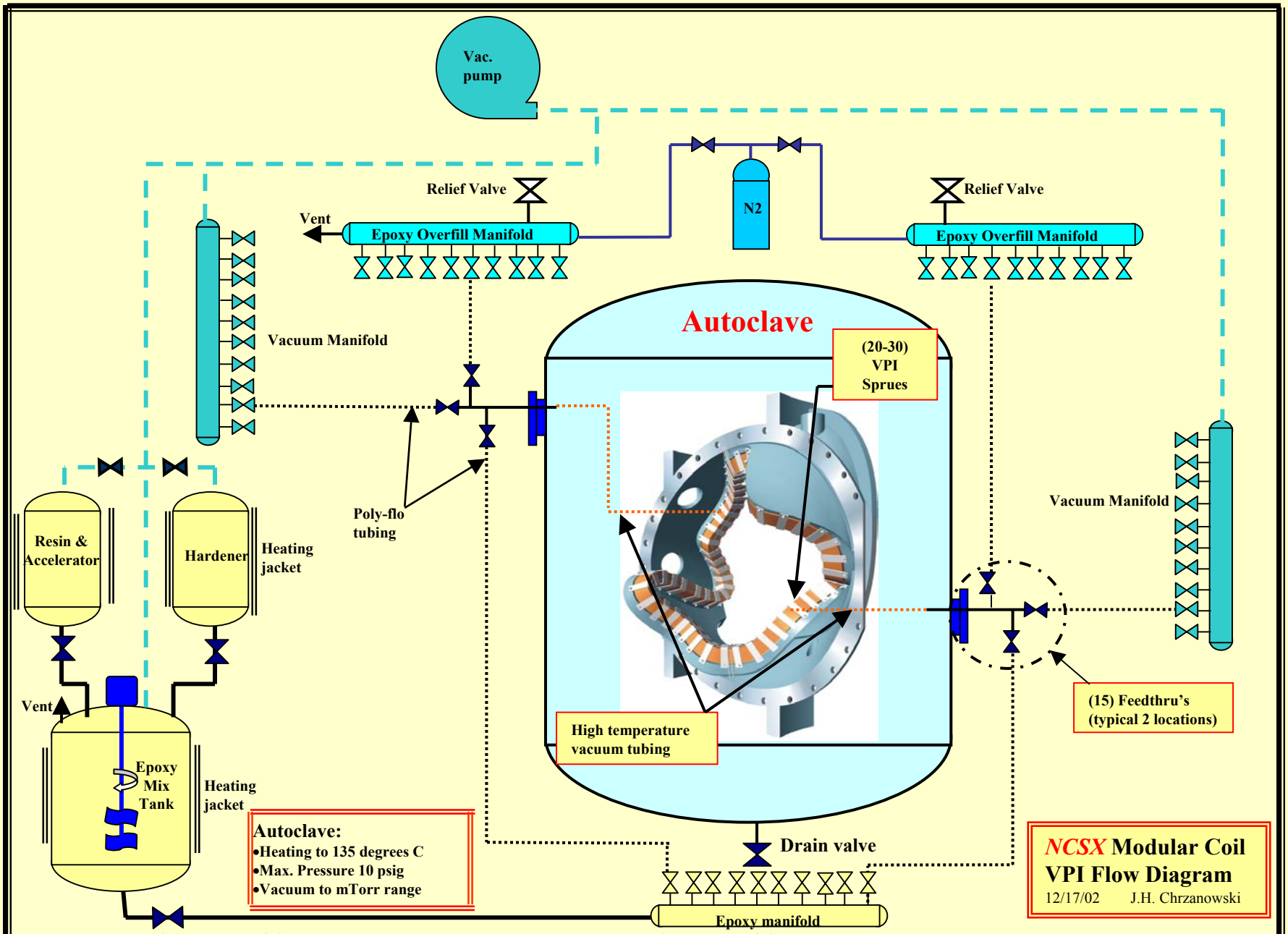


VPI System Description

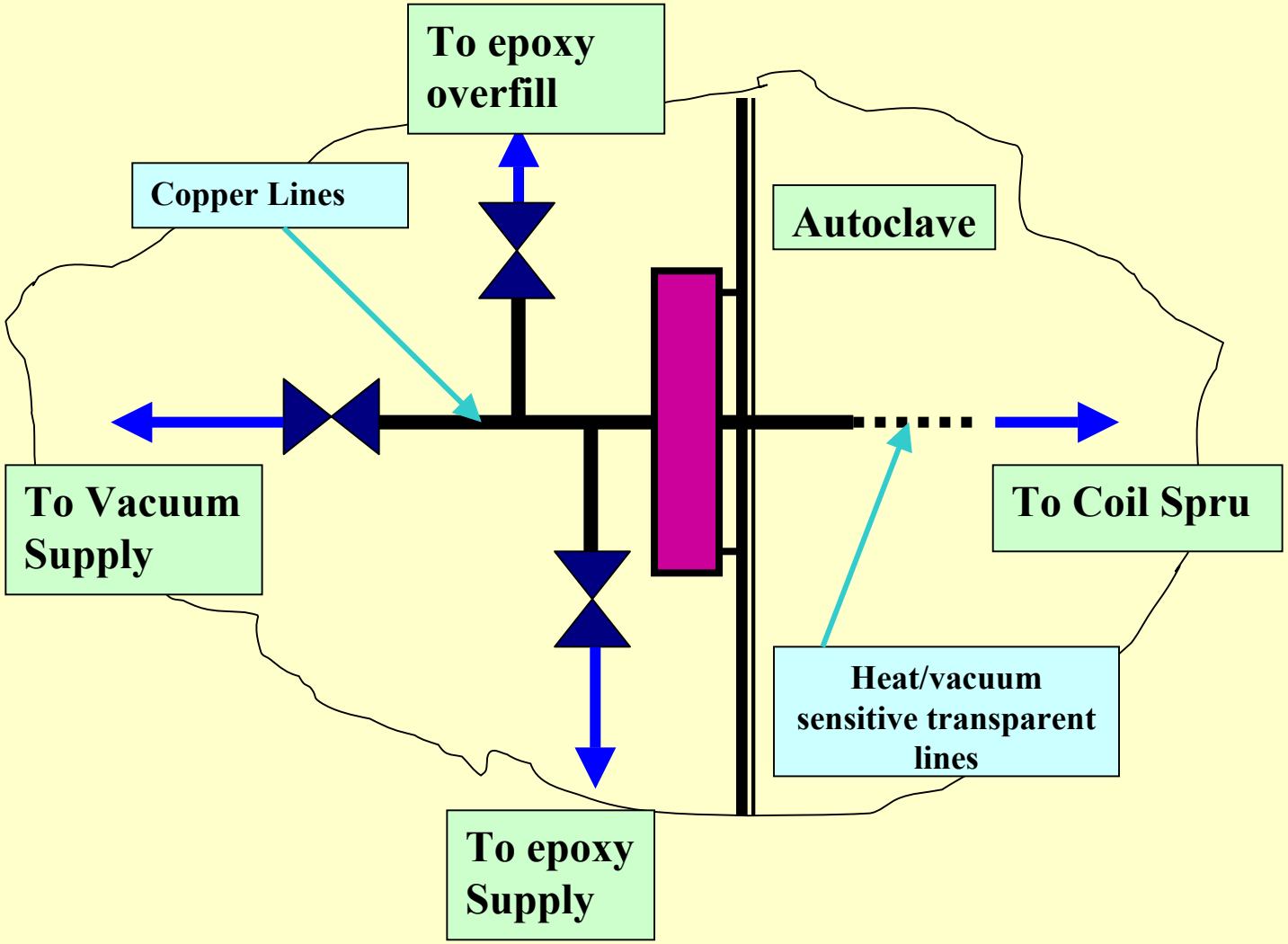
- A system for required for the preparation, delivery and curing of a selected epoxy that will be introduced into the modular coils during VPI.
- System requirements:
  - Capable of handling the epoxy components including component weighing, mixing and degassing
  - Capable of providing the heat necessary to cure the impregnated coils
  - Vacuum system for evacuating the mold and autoclave
  - Pressure system to be used during the soak period
  - Measurement system for monitoring temperatures, vacuum, pressure and viscosity

Equipment for VPI Program

- Autoclave (vacuum bakeout oven)
- Oven temp. controller
- (1) 30 gallon mixing tank
- (2) 15 gallon degassing tanks
- Epoxy mixing equipment
- Epoxy overflow manifold
- Viscosity measuring equipment
- Molded modular coil
- Vacuum pump
- Vacuum manifolds
- Nitrogen pressure supply
- Leak Detector
- Epoxy manifold system
- Epoxy weighing
- “Scrambled Egg” Test equipment

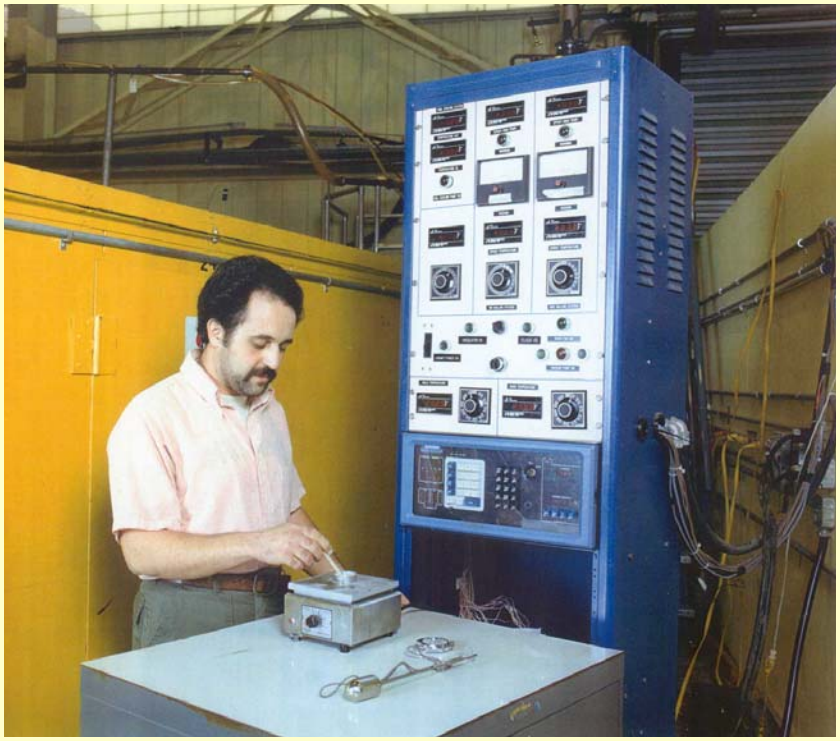

Vac. pump
Relief Valve
Vent
Epoxy Overfill Manifold
N2
Relief Valve
Epoxy Overfill Manifold
Autoclave
Vacuum Manifold
(20-30) VPI Sprues
Poly-flo tubing
Resin & Accelerator
Hardener
Heating jacket
Vacuum Manifold
Vent
Epoxy Mix Tank
Heating jacket
High temperature vacuum tubing
(15) Feedthru's (typical 2 locations)
Autoclave:
•Heating to 135 degrees C
•Max. Pressure 10 psig
•Vacuum to mTorr range
Drain valve
Epoxy manifold
NCSX Modular Coil VPI Flow Diagram
12/17/02 J.H. Chrzanowski

VPI System Description



VPI Process- Epoxy Verification

- **"Scramble Egg Test"** will be used to verify the correct mixture of components prior to introducing the epoxy to the coil.
  - A quart of epoxy will be dumped from the bottom of mixing (fill) tank following the mixing operation. Then a small quantity of epoxy will be taken from the tank for testing.
  - The sample contents will be placed on a hot plate pre-set at the cure temperature and stirred continuously until gelling occurred.
  - If the mixture does not began to gel within predetermined time, the entire batch of epoxy would of been discarded and dumped.



VPI Process Description

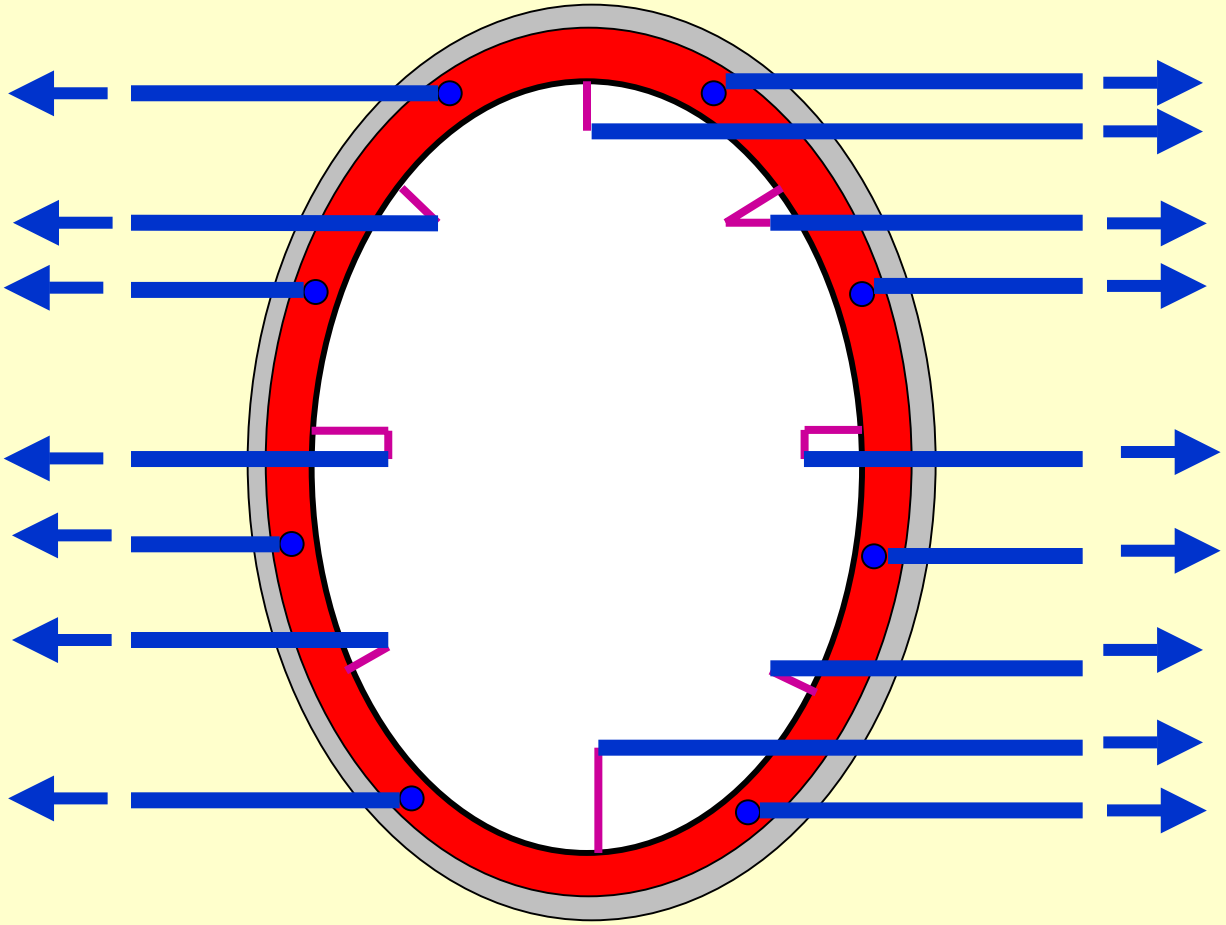
- Maintain a 0.5 to 1 Torr vacuum on the mold and Autoclave
- Maintain the mold and coil temperatures at 40-45°C
- Mix epoxy components and degass (2 to 3 Torr)
- Fill the coil- Once all of the exit ports have evidence of epoxy, the pressure on the fill tank will be removed and brought to atmosphere.
- "Milking" Process- Raise pressure on vent manifold to 3 psig max. and move epoxy no closer than 3 inches from the mold.
- Remove pressure and apply 0.5 to 1 Torr vacuum to the overfill manifold. Repeat milking steps until there is no evidence of bubbles in the lines.

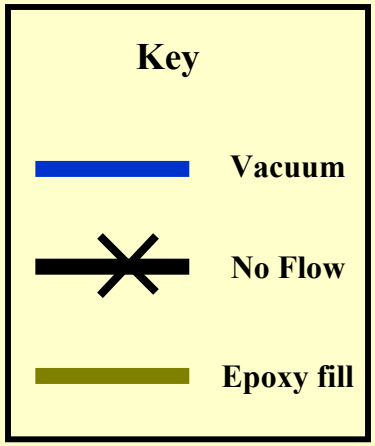
VPI Process Description

- Apply 3 psig (max.) on fill tank and 1 Torr vacuum on the overflow manifold and continue filling until all of the exit lines are filled to at least 8 feet away from the mold
- Apply 1-3 psig pressure on coil and autoclave (Soak/Gel time) while ramping up to cure temperature (110° C) and hold for 16 hours
- Remove pressure once epoxy has Gelled
- Ramp up to Post-Cure temperature (125° C) and hold for 5 hours at temperature
- Ramp down coil temperature to room temperature

VPI Process- 1. Pre-epoxy

Pull a vacuum on entire coil



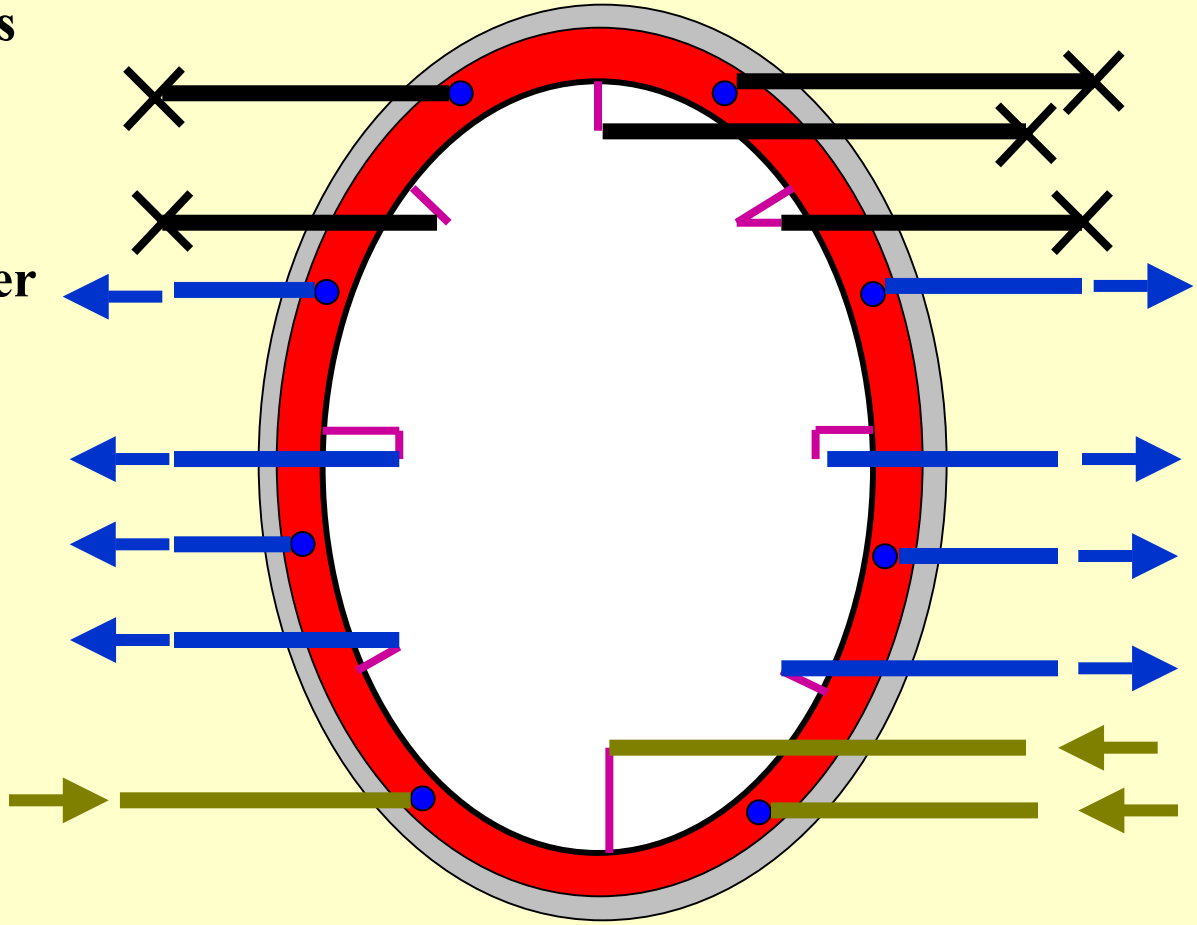


VPI Process- 2. Begin Epoxy Fill

Introduce epoxy through lower Sprues

No vacuum on upper coil end

Vacuum on remainder of coil

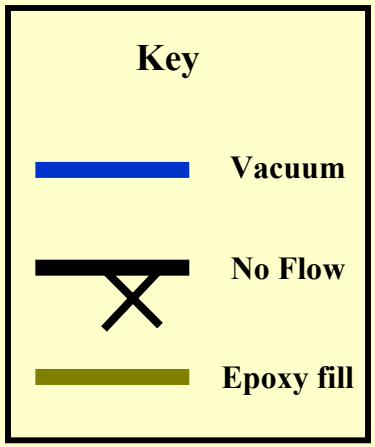


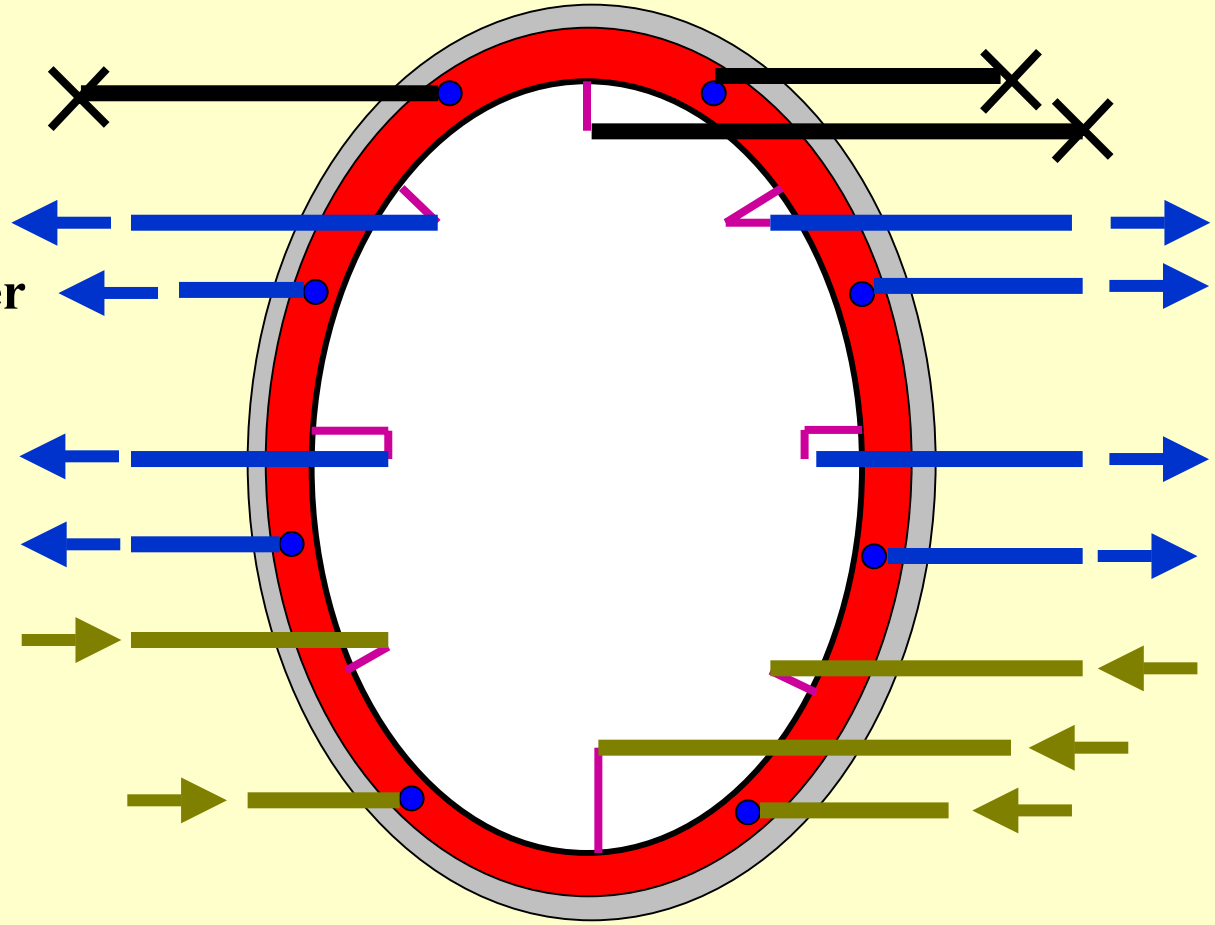
VPI Process- 3. Continue Epoxy Fill

Introduce epoxy through additional lower Sprues

No vacuum on upper coil end

Vacuum on remainder of coil- more upper Sprues added



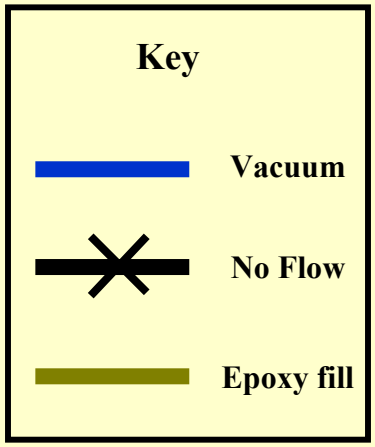


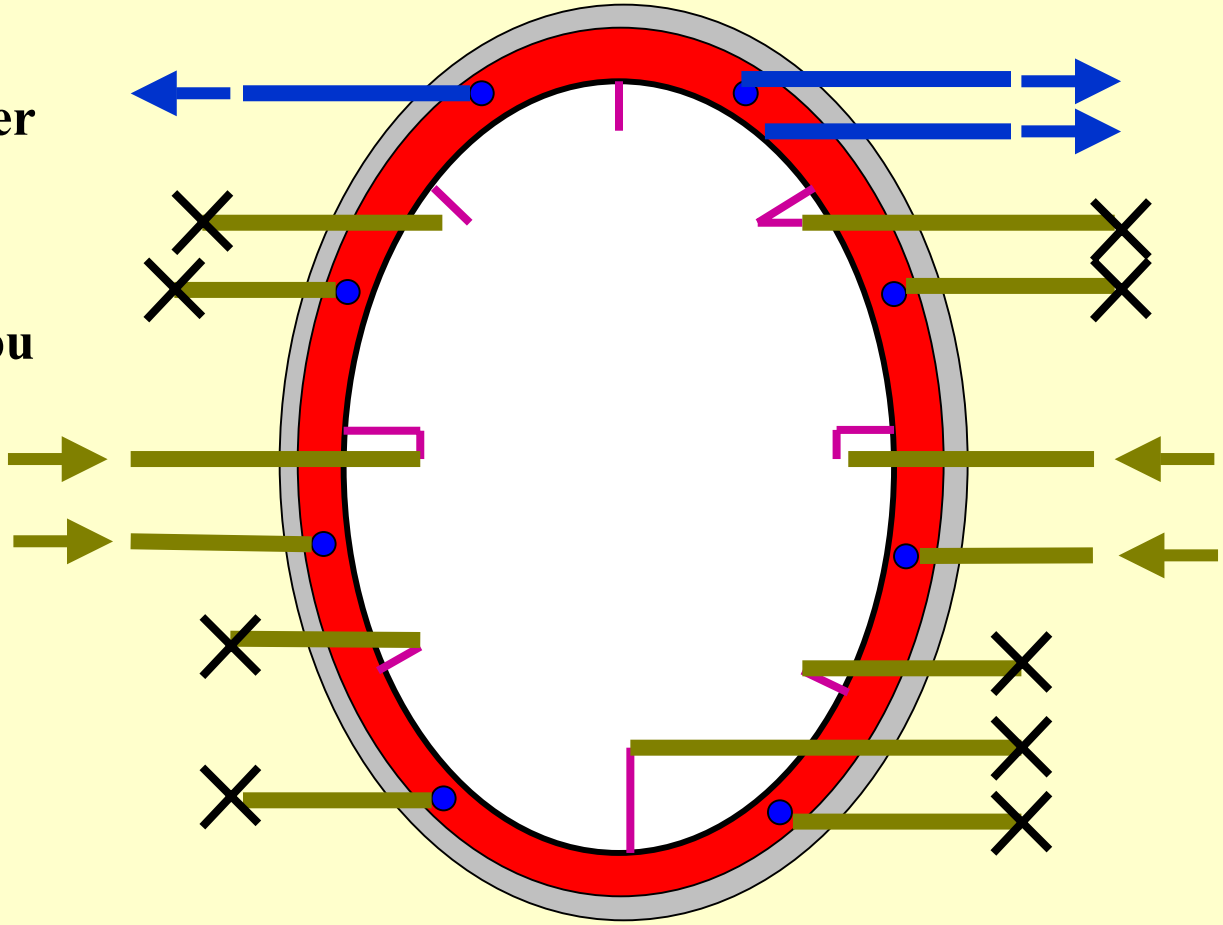
VPI Process- 4. Continue Epoxy Fill

Introduce epoxy through mid level Sprues

Vacuum on remainder of coil

Continue to walk up the fill points until you reach the upper quarter



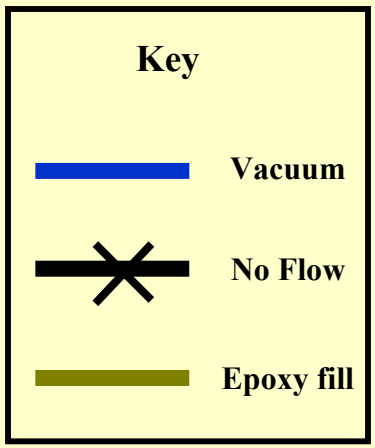


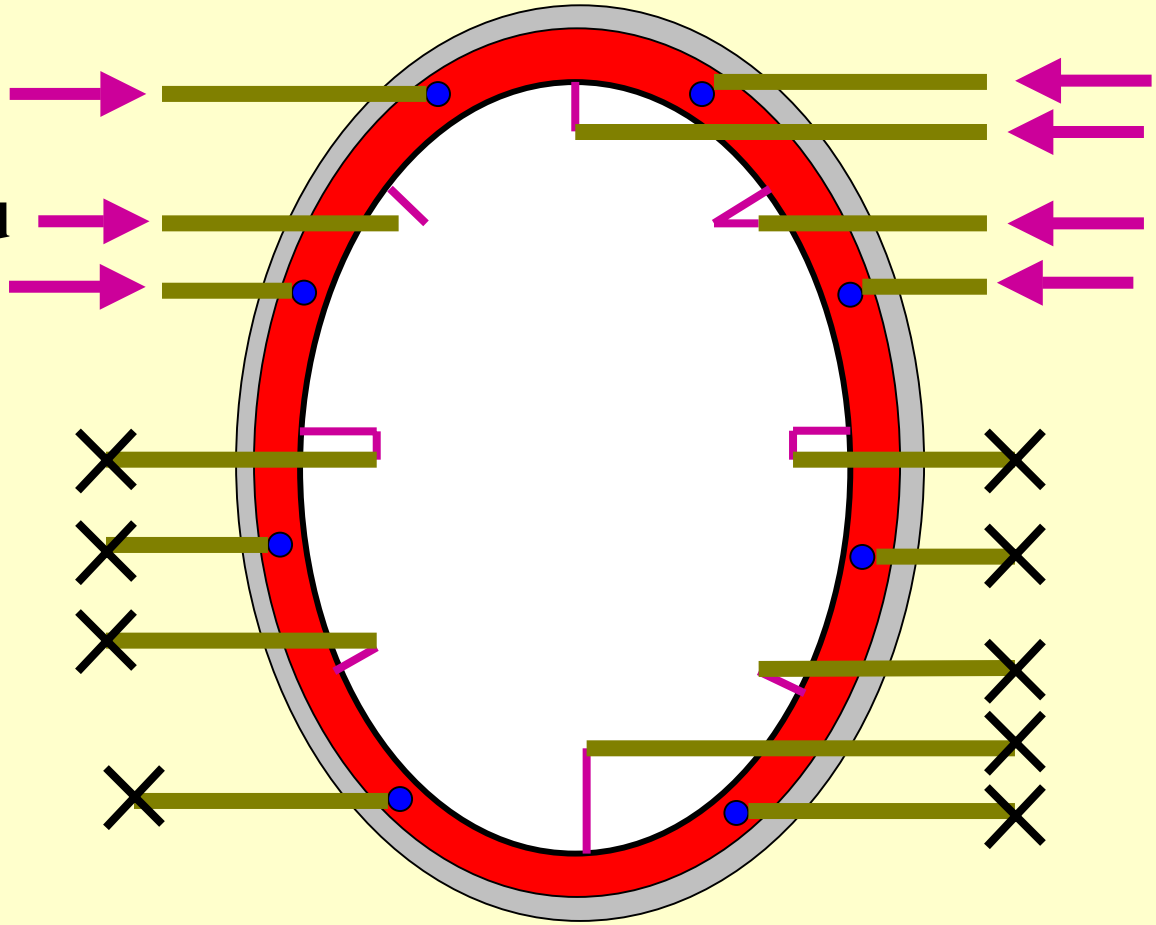
VPI Process- 5. Coil Filled/Soak Period

Coil totally filled

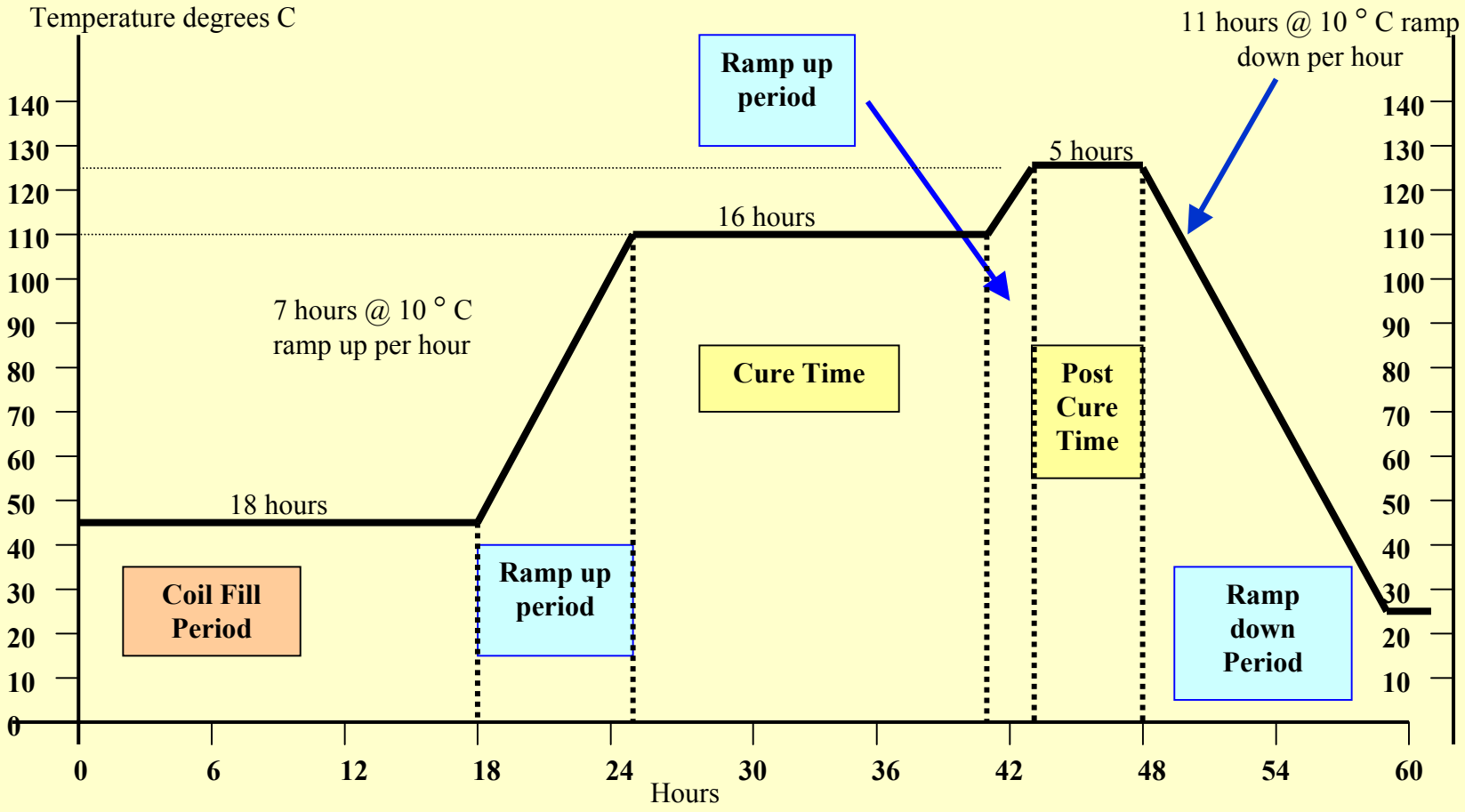
Pressurize upper third to 1-2 psig

Begin ramping up temperature





NCSX MODULAR COIL VPI CYCLE



J. Chrzanowski 1/14/03

VPI Process Time

- **Duration of Mold Assembly and VPI Process**
  - Assemble mold…… 3 days
  - Mold prep in oven ……... 3 days
  - Vacuum pull down …….. 2 days
  - VPI Cycle
    - Fill coil ……. 1 day
    - Ramp up to Cure temp…….. 1/2 day
    - Cure and ramp up to Post cure temp……. 1 day
    - Post cure and ramp down ……. 1 days
    - Coil removal from oven ……... 1 day
    - Oven prep for next coil …… 2.5 day

Total Duration per coil …. 15 days

Duration between coils (Autoclave usage).. 12 days

VPI Process-Expendable Supplies Per Coil

- **Epoxy Usage**
  - 8 gallons per coil
  - 3 gallons in fill lines plus 4 gallons reserve
  - **15 gallons total**
- **Fill lines**
  - In-oven (High temperature vacuum tubing)…. 250 feet
  - Outside oven (Vacuum tubing) ……... 250 feet
- **Manifolds**
  - (1) Rebuild epoxy fill manifold replace valves (30)
  - (1) Rebuild epoxy overfill manifold replace valves (30)
- **Epoxy Feedthru's**
  - Replace all feed-thru's through the autoclave 3wall 25-30