NCSX
"Modular Coil VPI Autoclave"
FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

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1.0 Description of Autoclave system

1.1 An autoclave is a pressure chamber used to cure materials at elevated temperatures and pressures, and/or vacuum during the process and cure cycles. The application and sequence of heating, cooling, pressure and vacuum are predetermined by the process specifications that detail the fabrication and treatment of parts.

The NCSX Modular Coil Autoclave has been specifically designed to accommodate the NCSX Modular Coils, and to provide the necessary operational parameters for the Vacuum Pressure Impregnation (VPI) process that is employed in the production of these coils.

1.2 Vacuum/Pressure requirements:

1.2.1 Pumpdown a base pressure equal to or less than 1 torr.
1.2.2 Pumpdown to base pressure in 4 hours or less.
1.2.3 Rate of rise (empty chamber, no pumping) to be less than 5 torr per hour.
1.2.4 Capable of withstanding 30 psia (15 psig) internal pressure.
1.2.5 Service ports

1.3 Heating requirements:

1.3.1 Circulating fluid (gaseous) heating system than can heat the modular coil sections to 50 degrees centigrade in 15-hour period.
1.3.2 Wall heating (resistive) capable of maintaining inner temperature (under vacuum) at $50^{+/-}2$ degrees centigrade.
1.3.3 Outer wall insulation.
1.3.4 Provide heated air for venting from vacuum condition.

1.4 Instrumentation and Control

1.4.1 Temperature readouts of:
1.4.1.1 Modular coil

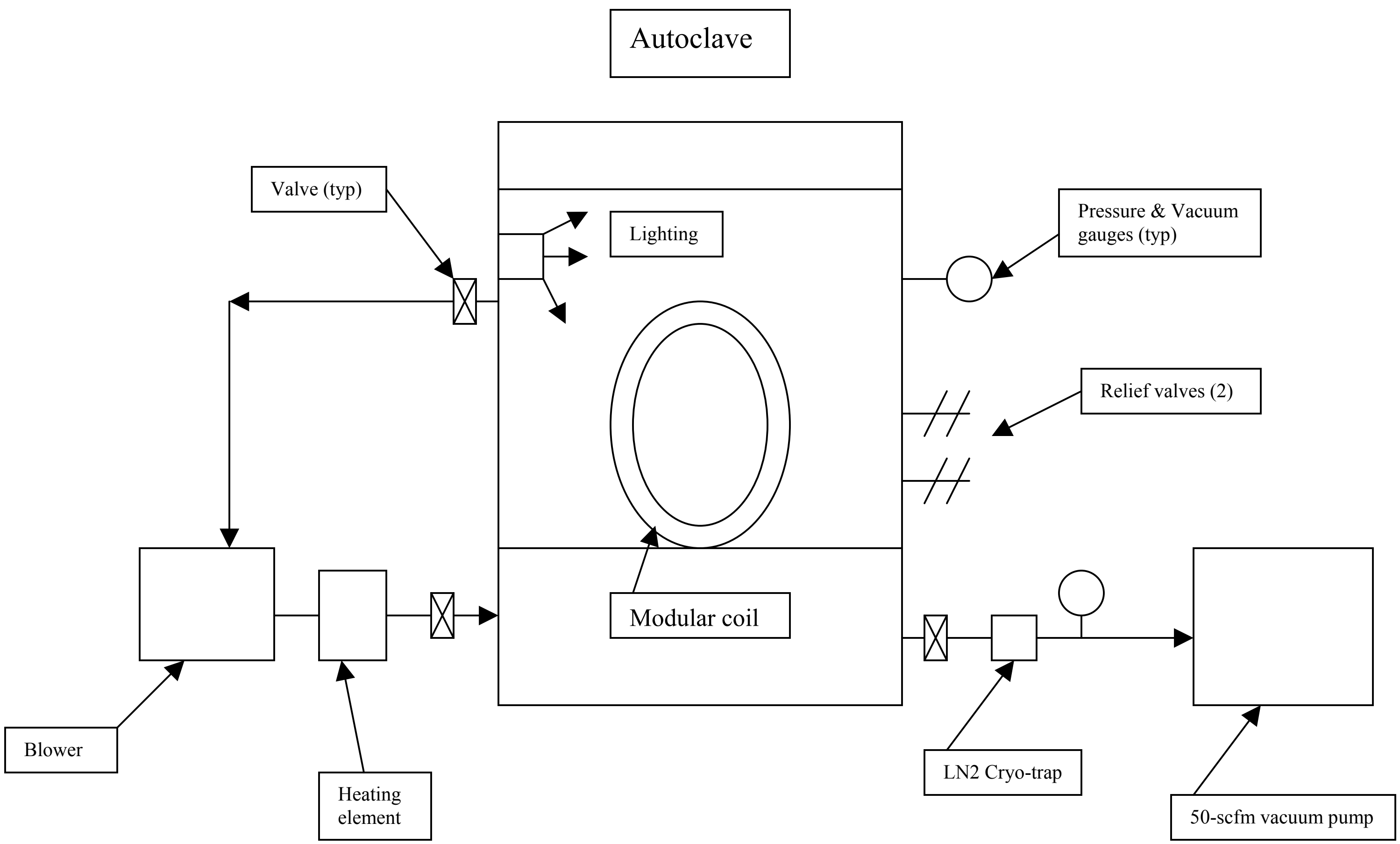
1.4.1.2 Autoclave walls
1.4.1.3 Internal air/fluid

1.4.2 Vacuum readout.
1.4.3 Feedback control of wall heating system
1.4.4 Feedback control of air circulating heating system

2.0 Operation (reference)

A typical cycle for the impregnation and curing of the modular coil conductor is as follows:

2.1.1 Remove autoclave lid, lower (wound) modular coil section into chamber and secure.
2.1.2 Connect epoxy sprus and thermocouple leads.
2.1.3 Install lid and secure.
2.1.4 Start vessel-heating system. Heat at a rate not greater than 10 degree centigrade per hour to a temperature of 40 C.
2.1.5 Initiate wall-heating mode to maintain coil temperature at 40 C while under vacuum.
2.1.6 Evacuate autoclave to a pressure of 0.5 to 1 torr
2.1.7 Initiate epoxy impregnation by directing flow to lower spru(s).
2.1.8 Observe through viewports as impregnation process proceeds. Valve in additional sprus as necessary.
2.1.9 Increase epoxy delivery pressure, as well as autoclave internal pressure correspondingly, as necessary to enhance epoxy flow.
2.1.10 Continue impregnation process until epoxy flows from top (exhaust) sprus. Valve off epoxy when coil is fully impregnated.
2.1.11 Vent autoclave with 40 degree C air to 0 psig.
2.1.12 Initiate heating system and heat at a rate not greater than 5 degree centigrade per hour to a temperature of 110 C.
2.1.13 Hold at 110 degree C for 5 hours.
2.1.14 Raise temperature to 125 degree C. Hold for 16 hours.
2.1.15 Turn off heating, and allow modular coil to cool.


Autoclave
Valve (typ)
Lighting
Pressure & Vacuum gauges (typ)
Relief valves (2)
Modular coil
Blower
Heating element
LN2 Cryo-trap
50-scfm vacuum pump

3.0 Purpose/Scope:

The goal of this FMEA is to identify failures that will compromise the success of the VPI Process. The scope of this FMEA covers that autoclave hardware and subsystems only. Failure of the VPI Process component/hardware will be addressed separately.

A compromise of the VPI process is further defined as a condition in which one of the following occurs. The VPI Cognizant Engineer shall ultimately decide whether or not the results of a VPI cycle are acceptable.

3.1 Failure of the impregnation process
- **3.1.1** Epoxy rich areas
- **3.1.2** Epoxy starved areas
- **3.1.3** Voids in the coil winding

3.2 Failure of the curing process
- **3.2.1** Epoxy leak from the bag-mold
- **3.2.2** Brittle condition after cure
- **3.2.3** Soft condition after cure
- **3.2.4** Cracks in cured winding

4.0 Description of FMEA columns.

4.1 Component - The piece of hardware or subsystem where the failure occurs.
4.2 Failure Mode/Cause - Description of the failure.
4.3 Effect on VPI process - The effect on the success of the VPI process. The Effect on VPI Process has been further defined in the following categories:
- **4.3.1** None. Has no effect on the VPI process and does not have to be repaired before next cycle.
- **4.3.2** Negligible. Has no effect on the VPI process, but should be repaired before next cycle.
- **4.3.3** Minimal. May have an effect on the VPI process, unless a compensating provision is taken.
- **4.3.4** Marginal. May or may not affect VPI Process, depending on severity and timing of failure.

4.3.5 Halt Process. Requires the VPI to be halted. The ramifications of halting the process are greatly dependant on the timing of the failure.

4.3.6 Other. This is a failure that should not affect the VPI Process, however it could affect the operators' ability to control or monitor the process.

4.4 Fault Detection/Isolation - This is the mechanism by which the failure will be detected

4.5 Compensating provisions - Describes action(s) taken to overcome the failure, typically without severely affecting the VPI Process. These options typically compensate for the failure by adjusting an operating parameter, or operating equipment in a different configuration, however, if the VPI process must be halted, there is no compensating factor

4.6 Remarks –additional information deemed relevant.

5.0 FMEA Analysis:

Project: __NCSX__ **FAILURE MODES AND EFFECTS ANALYSIS** page _______ of_________

Element: **Autoclave for Modular Coil VPI** Performed By: **Steve Raftopoulos** Date: ______________

Component: ____________________________ Reviewed By: ____ Date: ______________

Component	Failure Mode/Cause	Effect on VPI process	Fault Detection/Isolation	Compensating provisions	Remarks
Vacuum Vessel	Small leak in weld	Minimal	Rise in tank pressure	Run 2nd pump	Re-weld or Glyptol
Vacuum Vessel	Large leak in weld	Halt process	Rise in tank pressure		Re-weld
Vacuum Vessel	Small leak in O-ring	Minimal	Rise in tank pressure	Run 2nd pump	Replace later
Vacuum Vessel	Large leak in O-ring	Halt process	Rise in tank pressure		
Vacuum Vessel	Failure of internal lighting	Other	Obvious failure	Use external lights at viewports	Unlikely all units fail simultaneously
Vacuum Vessel	Failure of the pressure relief valve	Minimal	High pressure reading	1:Redundant relief valve 2: Procedural control	
Vacuum Vessel	Window failure	Halt process	Obvious failure		Very, very unlikely
Vacuum system	Failure of vacuum pump	Minimal	Rise in tank pressure	Operate backup pump	
Vacuum system	Failure of vacuum gauge	None	Loss of data/readout	Redundant gauge	Replace later

Vacuum system	Failure of vacuum cryotrap	Minimal	Periodic monitoring per procedure.	Periodic monitoring per procedure. Install dry coalescing filter upstream	Contamination of pump oil
Heating system	Failure of heating element	Negligible	None	Fix when not operating	
Heating system	Failure of multiple heating elements	Marginal	Temperature rise slower than usual	Elements wired in banks.	May or may not halt VPI depends on timing & severity of loss
Heating system	Failure of circulating fan/blower	Marginal	Audible detection of no blower/fan	Monitor multiple T/C for temp distribution	If temp distribution is OK, continue VPI at slower ΔT ramp-up
Heating system	Failure of thermocouple	Loss of data	No readout	Redundant T/Cs	
Heating system	Failure of thermocouple controller (low)	Loss of heating	No readout, readout does not match redundant units	Switch to one of redundant T/Cs and controllers	Periodic monitoring per procedure.
Heating system	Failure of thermocouple controller (high)	ΔT ramp up too fast	T/C data will alert operators	Operate manually or switch to alternate unit controller	Periodic monitoring per procedure.

6.0 Conclusions

The following design features are incorporated to address the areas the areas of concern identified by the FMEA.

6.1 Redundant vacuum pump. A back-up pump will be installed and available to provide redundancy in the event of failure of the first vacuum pump and to provide additional pumping speed in the event of a small vacuum leak.

6.2 Redundant thermocouple controllers. Redundant controllers are available for use as backup to the feedback controller. Typically, several controllers are used as readout devices, but are not used in the feedback control for temperature. In the event of failure of the controlling device, one of the controllers acting as readout can be converted into feedback control mode.

6.3 Redundant vacuum and pressure gauges. Although these gauges are not part of a feedback control system, they provide operators with the data required to run the VPI process. Redundant gauges ensure that this data is not lost during the VPI cycle.

6.4 Pressure relief valves. These provide an upper limit to the pressure that can be achieved in the autoclave. The pressure in the tank is controlled both administratively (the bottle regulator will be set per procedure) and by engineered hardware (the relief valves). Redundant relief valves ensure that a single point failure does not overpressure the tank.