# NCSX Vacuum Vessel Systems

# Failure Mode and Effect Analysis (FMEA)

# NCSX-FMEA-12-001-00

July 31, 2006

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**Subject:** **NCSX FAILURE MODES AND EFFECTS ANALYSIS (FMECA)**

**Originator:** P Goranson **Date:** July 31, 2006
**WBS Element:** 121
**Component:** Vessel and Vessel Sub-systems

**Summary**
The following requirements and recommendations are derived from the FMECA analysis for NCSX WBS 1.2 Vacuum Vessel. They are provided to assure safe and reliable operation of the VV and it's systems during normal operations and during off-normal events.

**Overview**
The vacuum vessel (VV) provides a high vacuum environment for plasma operation. Purity will be maintained by bake out of the vessel to 350 C. The port end flanges will be maintained at 150 C during the bake out. The VV and ports will be maintained at 21-80 C during operation. Temperature control of the vessel is via coolant tube/hose tracing attached to the outer surface of the vessel and resistance heaters on the port extensions. Schematics in the Appendix show the recommended cooling/heating system and the temperature control system, including the control logic.

**1. Failure mode:** Coolant tracing(s) leaks.

Failure cause/mode:
a. a small leak at a weld fitting
b. a pin hole in a line
c. a catastrophic failure of a tube with release of pressured helium into the cryostat.

<u>Fault detection/Isolation:</u>
The following systems should be provided:
Pressure sensors in the helium system to detect large leaks and shut down the system, closing off helium supply.
The cryostat should be monitored with helium detectors.
A burst disc in the cryostat to prevent over-pressurizing.
The VV coolant system is fabricated in two parallel system and valves should be provided to isolate them so operation of one may continue while the other is shut down and repaired.

<u>Comments:</u>

The individual coolant lines on the VV may be disconnected at the headers and checked for leaks. A defective line could be plugged and the system continue to operate with little degradation in performance. This is studied in detail in the DAC NCSX-CALC-12-001 on Local Heating and Cooling.

**2. Failure mode:** VV leaks.

Failure cause/mode:
A faulty port seal is the most likely cause, a port extension weld failure is less likely and a torus shell or sector to sector assembly weld is much less likely

<u>Fault Detection /Isolation:</u>
A mass Spectrometer should be incorporated into the VV vacuum system to monitor for off-normal levels of atmospheric gases.

<u>Comments:</u>
Port seals are accessible for bagging and conventional helium leak checking
Port extensions are provided with leak check tubes, attached at weld joints and lead out to the flanges. Welds may be leak checked anytime in the future by supplying helium to the tubes and sensing the VV interior vacuum.
Leaks in the torus shell or assembly weld will require special compliant boot to apply local vacuum connected to leak detector

**3. Failure mode:** Tracing does not cool down VV in specified time

Failure cause/mode:
Insufficient coolant flow, coolant pressure, or excessive temperature level in coolant

<u>Fault Detection /Isolation:</u>
Thermocouples, pressure gauges, and flow meters should be provided to monitor coolant temperature, pressure, and flow in the VV supply headers, ahead of, and after, the VV.

<u>Comments:</u>
Cooling power could be boosted and coolant could be sub-cooled to compensate.
Calculations in DAC NCSX-CALC-12-002 were done to determine cool down time

**4. Failure mode:** Port flanges overheat or do not maintain proper temperature

Failure cause/mode:
Resistance heater malfunction.
Heaters not set properly

<u>Fault Detection /Isolation:</u>

Circuits and controllers are separate for all ports. Detection will be loss of current in circuit.
Thermocouples will monitor temperature in each port extension.
An automatic system should be utilized to alert the operator and shut down automatically if any temperatures exceed critical threshold.
The heaters should be of the proportional voltage type, not the on-off variety. This would prevent large temperature excursions and provide a longer reaction time for the operator.

Comments:
Heaters run at only 10-20% capacity and should have long life.
The thermal time constant is long and there is warning long before parameters become critical. Ports 12 and 4 each have four independent heater zones
Power to heaters may be boosted.
Heaters and thermocouples are redundant
Calculations were performed in DAC NCSX-CALC-12-003 to determine port temperature.

**5. Failure mode:** Tracing does not heat VV to 150 C during operation or fails to heat to 350C during baking.

Failure cause/mode:
Insufficient flow, pressure, or temperature in coolant.

Fault Detection /Isolation:
Captured by Failure Mode 3, above.

Comments: Alternate means such as inductive heating may be used to augment baking.

**6. Failure mode:** Loss of VV cooling/heating

Failure cause/mode:
Facility power interruption or equipment failure resulting in loss of coolant flow to VV and/or power to port extension heaters.

Fault Detection /Isolation:
Thermocouples warn of critical temperatures.
Backup power supply could be used to keep port extensions warm.
Venting to atmosphere and circulating air through vessel or turning up port heaters (if power available) could prevent a critical temperature situation.

Comments:
Ports with CF flanges terminate inside the cryostat during MIE operation and excursions down to 80 K are possible in the event of a system failure, but analyses have shown they can safely tolerate such an event. The VV thermal time constant is long and provides ample reaction time to take corrective action if desired.
The NB port, port 12, and port 4 terminate outside the cryostat and calculations indicate the flanges will not reach a critical temperature.

**7. Failure mode:** Helium pumping system or heating system over-pressures

Failure cause/mode:
Malfunction in a pump or regulator

Fault Detection /Isolation:

Piping system should incorporate pressure and temperature sensors and be programmed to automatically shut down if failure is detected.

Rupture disks in headers should be provided as backup and would relieve system before damage is possible, if all else fails.

References

NCSX-CALC-12-003

Vacuum Vessel Heat Balance Analysis

NCSX-CALC-12-002

Vacuum Vessel Heating/Cooling Distribution System Thermo-hydraulic Analysis

VV Local Thermal Analysis

NCSX-CALC-12-001

**APPENDIX** FAILURE MODES AND EFFECTS ANALYSIS WORK SHEET

Project: **NCSX**

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WBS Element: 121

Performed By: P Goranson

Date: July 20, 2006

Component: Vessel and vessel sub-systems

Reviewed By:

Date:

Function: The vacuum vessel provides a high vacuum environment for plasma operation. Purity will be maintained by bakeout of the vessel to 350 C. The port end flanges will be maintained at 150 C during the bakeout. The VV and ports will be maintained at 21-60 C during operation. Temperature control of the vessel is via coolant tube/hose tracing attached to the outer surface of the vessel and resistance heaters on the port extensions. Attached schematics show the cooling/heating system and the temperature control system, including the control logic.

| **Operating Mode** | **Failure Mode /Cause** | **System Effect** | **Fault Detection /Isolation** | **Compensating Provisions** | **Remarks** |
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| Bakeout and cool down during operation. | Coolant tracing(s) leak.<br>a. small leak at weld fitting<br>b. pin hole in line<br>c. catastropic failure of tube with release of pressured helium into cryostat. | a,b. System can operate satisfactorily with loss of one or two tubes per period, or with small degradation of performance with loss of one of the two field period circuits. Very small leak (1e-4 torr-l/s) of helium into cryostat is acceptable.<br>c. overpressure and potential structural failure of cryostat | Pressure sensors in the helium system will detect large leaks and shut down the system, closing off helium supply. Monitoring cryostat with halogen detectors. | a,b. . Each of the three field periods has two separate helium supply circuits, with 16 parallel flow coolant tubes. Leaking tubes may be isolated from system , by cutting and plugging. Remaining tubes may be run at higher heat.<br>c. burst disc in cryostat to prevent over-pressurizing | Welds are accessible for repair, tubes are not. System is leaked checked before final installation to detect any potential problem. System pressure is very moderate. Leaks are unlikely to develop in body of Inconel tube. Material is ordered under ASTM specification to assure quality and has high |

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| | | chamber. | | | factor of safety. |
| Off normal<br>a. disruptive operation.<br>b. seismic event | Failure of VV structure. | Loss of device with long shutdown for repairs. | Seismic detection and shutdown of facility. | Large safety factor in structural design. Strict criteria for dead weight on ports. Use of Inconel to limit eddy currents in VV during disruption. Electrical breaks in shell and support equipment. | Two independent analyses of structure with peer review and calculation checks to certify the analyses. Methods proven in past designs. Seismic criteria for region is available. |
| Final assembly | Modular coils do not assemble over vessel. | Large impact on project cost and schedule. | Vessel contour is monitored after each critical step of fabrication. QA plan provides feedback with vendor supplying step files back to PPPL for recheck before fabrication proceeds. | Ample toerance are being provided for assembly clearance. Out of tolerance features will be detected early and corrected when cost impact is small. | Assembly is being checked by multiple means: stereolithography scale models, computer mathematical models, and 3-D graphics models. |
| Operation | a. VV leaks.<br>b. Port extension weld leaks. | Leaks can result in large delays in operation and costs to project. Even small leaks can compromise device operation. | a. Vessel will be leak checked during fabrication and baked out to detect leak development before installation. Welds will be inspected and radiagraphed. Leaks may be tracked down by flooding several independent sections | Use of national welding standards, qualified welders, and certified materials. Man access into VV interior will provide cabability to detect and repair both VV wall and port extension welds from the inside. | Thick walled vacuum vessels with full penetration welds have good history of reliability. Visually approved welds in Inconel usually are leak tight. |

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| | | | of VV exterior with helium under the insulation. Perforated tubes are provided on VV surface for this purpose. Technician can access interior with portable leak detector which sniffs wall.<br>b. Port extensions are provided with collars around weld area during assembly. Leak check tubes are attached to these collar and lead out to the flanges. Welds may be leak checked anytime in future by supplying helium to the leak check collars and sensing VV interior vacuum. | | |
| Operation | VV does not pump down to specified level due to virtual leaks. | System could fail to meet design criteria, acceptable operation regime may not be achieved. | Use of code full penetration welds on vessel; welds are performed on outside with root pass inside. Inspection and leak checking to detect | Access into the vessel permits repair of defects. | Long experience in high vacuum design minimizes risk. |

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| | | | porosity. Leak detection provisions built into VV field joints. | | |
| Operation | Tracing does not cool down VV in specified time. | System could fail to meet design criteria. Slower operation cycle and delay in data collection. | Thermocouples on VV and flanges. | System is robust. Cooling power could be boosted and coolant could be sub-cooled to compensate. R&D testing of system done to confirm cooldown calculations. | Mutiple dependent calculations done with peer review, to confirm operation times will meet criteria. |
| Operation | a. Port resistance heater(s) fail.<br>b. Required temperature not achieved.<br>c. Port flanges overheat due to resistance heater malfunction. | a, b Cold operation of port extensions, increase in vacuum impurity. Possible compromise of operation could result.<br>c. Failure of flange weld and loss of vacuum. | a.,b Circuits and controllers are separate for all ports. Detection will be loss of current in circuit.<br>c. Thermocouples will monitor temperature in port extensions. | a. Redundant heaters supplied during assembly. Heaters can be added to port inside[vacuum side] of port if both heaters lost on port. Heaters on outer port extension would also be adequate to bring system into operation envelope.<br>b. System is robust. Power to heaters may be boosted.<br>c. Automatic system will alert operator and shut down automatically if temperatures exceed critical threshold. | Heaters run at only 10-20% capacity and should have long life. The thermal time constant is long and there is warning long before parameters become critical. Ports 1 and 4 each have four independant heater zones |
| Bakeout | Tracing does not heat VV to 350C. | Increase in vacuum impurity due to | Thermocouples will monitor VV | Tracing design is robust. Operating temperature, flow, | Mutiple dependent calculations done with |

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| | | incomplete bakeout. Possible compromise of operation results. | temperature. | or pressure may be increased to compensate. Alternate means such as inductive heating may be used to augment baking. | peer review, to confirm operation times will meet criteria. |
| Bakeout | Interference between VV and structures such as shell and cryostat due to differential thermal growth. | Possible damage to VV or other components. | Early studies and analyses to assure proper clearances and characterize differential thermal growth. | Liberal clearances between VV and srtructures. | |
| Operation during CD3. All port flanges except 4 and 12 end within the cryostat | Facility power interruption resulting in loss of coolant flow to VV and/or power to port extension heaters. | VV cools down to cryogenic temperature. O-ring seals in NB port lose compliance and could result in vacuum leaks. Attachment welds on the other vessel flanges are vulnerable to fail due to expansion differences in the stainless and Inconel. Repair would require partial dismantling of Cryostat. | Early studies and analyses to characterize differential thermal stress, and determine critical thresholds. Thermocouples to warn of critical temperatures. | Backup power supply could be used to keep port extensions warm. Venting to atmosphere and circulating air through vessel or turning up port heaters could prevent a critical temperature situation. | DAC-121-TBD indicates that only non-circular ports with dissimilar material welds, terminating within the cryostat will reach critical stress level temperatures. There are no ports that are in this category. Ports with CF flanges can safely tolerate excursions down to 80 K. The VV thermal time constant is long and provides ample reation time to take corrective action if desired. Small leakage through NB o-rings is acceptable and easily |

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| | | | | | corrected; probably reseal after temperature control regained. |
| Modualar coil(MC) replacement. | Failure in a MC requires replacement. | Long term shut down of facility and dissassembly of VV field periods to permit removal of MC. | NA | VV uses spacers which may be cut free at each joint to permit removal of field periods. The cutting may be done with plasma torch, grinder or cutters. Threaded holes are provided on the flange interior for mounting fixtures which would facilitate cutting process. Some port extensions will also require removal by cutting with grinders or cutting tools. All work is done from the interior of the VV. | The VV would be refaced after the cutting process, the new gap geometry calculated, and a new spacer machined and welded into the assembly. The port extensions would also be re-preped and welded back into assembly. |
| Operation and/or bakeout | Malfunction in helium pumping system or heating system over-pressures and fails piping/tubes. | Failure of VV coolant tubes, which can not be replaced, necessitates shutdown of core sytem and dissassembly. | System pressure and temperature is monitored. | Piping system incorporates pressure and temperature regulators and is programmed to automatically shut down if failure is detected. Rupture disks in headers are backup and would relieve sytem before damage is possible, if all else fails. | Piping system has a large margin of safety and tight control is not critical. |

## VACUUM VESSEL TEMPERATURE CONTROL

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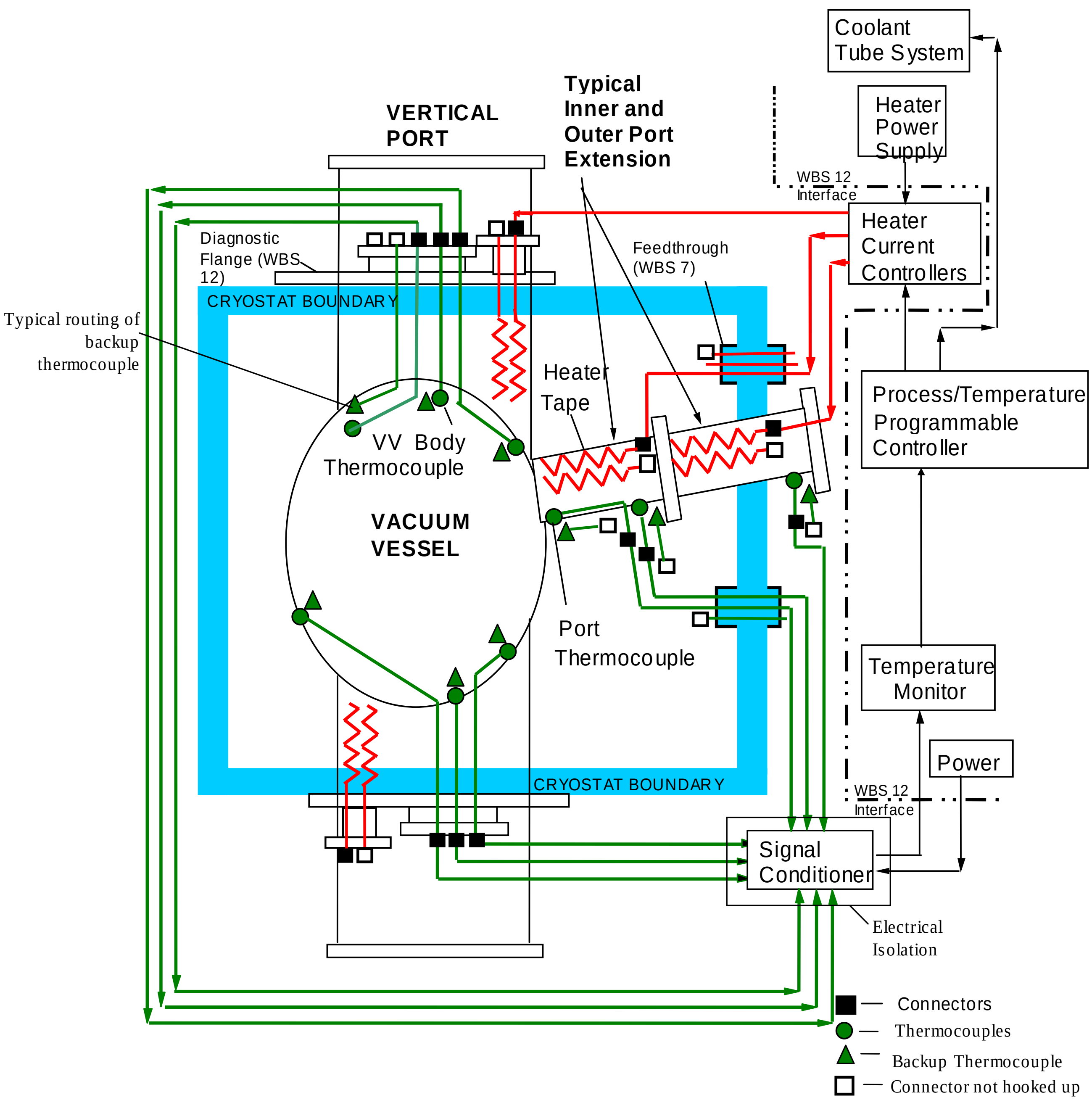

**VACUUM VESSEL HELIUM COOLING SCHEMATIC**
**Diagram is for full Field Period**