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Criteria for nomination:

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Development of an EPICS-based Vacuum Control System for the Caltech 40-meter LIGO Prototype Upgrade

Ted Jou
Dr. Alan Weinstein, mentor

Summer 1999

Abstract

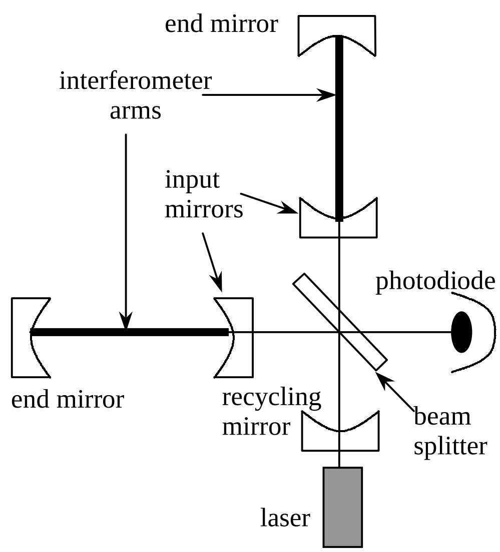
The current vacuum control system on the Caltech 40m LIGO prototype is an outdated Labview application that requires a significant amount of manual operation. As part of the general upgrade of the 40m LIGO prototype, this vacuum system needs to be replaced with a more modern one that interfaces with the rest of the LIGO/40m control system. The purpose of this project is to develop that control system using the EPICS platform following LIGO CDS (Control and Data Systems) standards to serve as the new control and monitoring system for the 40m vacuum. The new system is capable of fully automatic control of the vacuum system during all standard modes of operation. It also allows monitoring of the vacuum equipment from remote locations as well as manual control from a console located at the interferometer. This system is reliable and robust, capable of maintaining the 40m vacuum for a long period of continued research in gravity wave detection.

Introduction

The Laser Interferometer Gravitational-wave Observatory project (LIGO) is a collaborative effort between Caltech and MIT scientists to construct and operate two facilities dedicated to the detection of cosmic gravitational waves. These facilities are located in Hanford, Washington and Livingston, Louisiana. The prototype for these two facilities is located on the Caltech campus and is used for testing various equipment configurations before they are implemented in the two main LIGO facilities.

The LIGO facilities are power-recycled Michelson interferometers (see Figure 1) with Fabry-Perot arms extending 4km perpendicular to each other – the Caltech prototype has 40m long arms. A laser beam is directed into the vertex of the arms, where it is split and passes through each arm, reflecting off a test mass at the end of each arm. When the arms are perfectly calibrated, the beams will return to the beam splitter such that they constructively interfere in one direction and destructively interfere in the other. A recycling mirror is placed on the bright end to send the light back into the arms and a photodiode is placed on the dark end. Normally, this photodiode will detect no signal. However, if the arms were distorted by a

Figure 1: Michelson Interferometer



passing gravity wave, a signal would appear in the normally dark side of the apparatus.

Gravity waves are ripples in space-time predicted by Einstein's 1916 general theory of relativity. However, these waves have never been detected and their direct measurement is the main purpose of LIGO. A gravity wave is emitted by accelerating masses, and a large gravity wave with a detectable signal could be emitted by interacting black holes or neutron stars. A gravity wave interacts with LIGO by distorting space-time, making one arm longer than the other. The expected difference in length caused by a gravity wave is on the order of 10^{-18} meters. The wavelength of light is about 10^{-6}m, mirrors contain atoms 10^{-10}m in diameter, and the ground microseismic activity of the Earth's crust is on the order of 10^{-6}m/Hz$^{-0.5}$, thus, LIGO has to be a very precise instrument.

Part of this precision involves keeping LIGO in a very high vacuum (10^{-9} torr). The 9000 m^3 vacuum chambers of each interferometer are by far the largest ultra-high vacuums ever constructed. They are essential to the success of LIGO because the presence of gas and/or hydrocarbons in the beam tubes could cause spurious signal, weaken the signal, or create noise. At high vacuum conditions, the majority of gas left in the chamber is hydrogen, which could affect the signal with:

- Index of refraction fluctuations putting the beams out of phase
- Gas molecules colliding randomly with the mirrors, moving them unpredictably
- Absorbing the beam or scattering the beam, causing loss of signal.
- Scattering the beam back into the detector, creating noise

A small number of hydrocarbon molecules also persist in the chamber, and they have the greatest effect on LIGO sensitivity by:

- Depositing on optics, changing their optical characteristics

The high-powered laser used in LIGO only multiplies these effects, thus making the vacuum absolutely essential to the sensitivity of the observatory. A complex system of pumps and valves is required to achieve and maintain this ultra-high vacuum and a degree of automation is necessary to control this system.

The current vacuum systems at the LIGO 40m prototype and at the LIGO sites are controlled with a manual electronic system. These systems require a vacuum operator to manually operate valves and pumps from a computer console. In the next upgrade of the 40m prototype, a fully automatic vacuum control system is being implemented. The purpose of this project is to develop the software side of this project: developing a database for controlling each individual vacuum device, writing code for a state machine that can automatically transition between vacuum states, and designed a graphical interface to allow easy operation of the entire system. This system then needs to be installed on the 40m LIGO prototype along with appropriate hardware upgrades.

Materials and Methods

The existing vacuum system on the 40m LIGO prototype consists of 3 rotary-vane roughing pumps, 3 turbomolecular pumps, 5 Ion pumps, and 1 cryopump along with numerous pneumatic valves and pressure gauges. A schematic of this system can be found in Appendix A. These components all work to keep the main chamber at high vacuum. This system was designed to be controlled by a Labview application that allows an operator to open and close valves, turn on and off pumps, and to read values on gauges from a compute console. The wiring for this system can be found in Appendix A

Most of the hardware shown in the Mark II Vacuum Schematic (Appendix A) is not being changed in the 40m upgrade. There are two different types of gauges used in the 40m vacuum system. The first type is the Pirani gauge, labeled P#, which is effective from atmosphere down to 10^{-4} torr. The second type of gauge is the Cold Cathode gauge, labeled CC#, which is effective from 10^{-2} torr down to 10^{-9} torr. Most of the valves are electronically-controlled pneumatic valves and can be divided into three main sections. The first section is the main vacuum plumbing, with valves designated as V#, where most of the pumps are located. The second section is the annulus, designated by VA#, which controls each of the 5 annuli. The third section is the monitoring section, designated by VM#, which contains the RGA and leak-detection hardware. There are also three valves around the Cryopump, designated VC#, which isolate the Cryopump from the rest of the system.

The 40m vacuum system is designed as a state machine (see Appendix A) with four main states:

1. All Off – the default state of the system: All valves are closed and all pumps are shut off in the event of an emergency. The new system implements a Temporary All Off state that shuts everything off but assumes the chamber remains in vacuum.
2. Vacuum Normal – the easiest maintainable vacuum: Turbopumps 1 and 2 pump on the chamber and Turbopump 3 pumps out the annulus volume.
3. Chamber Open – used when the chamber needs to be opened to add new optics or make other changes: The chamber is held at atmospheric pressure while the turbopumps continue to run, holding the vacuum tubing at low pressure in preparation for pumpdown.
4. Vibration-Free Pumping – for high-precision measurements: The turbopumps (prone to vibration) are turned off and Ion pumps are used to pump out the chamber and the annulus.

A more detailed description of the states can be found in Appendix D. The definition of these states is not altered in the upgrade, but their implementation is. In the current system, an operator performs the transitions between the vacuum states by either clicking on the Labview interface or operating vacuum equipment manually. The software performs checks during these transitions to make sure the operator is following the correct procedure. The numerous checks and safeguards in the Labview system do very well to prevent catastrophes, but it is inconvenient and requires constant monitoring by a local operator.

The Labview system is primitive compared to the current suspension and optics controls currently implemented at the 40m. These were all designed by CDS (Control and Data Systems), a division of LIGO currently in charge of developing control systems for all the different parts of LIGO. CDS designed the manual electronic vacuum control systems at the LIGO sites and all other LIGO control systems using a platform called EPICS (the Experimental Physics and Industrial Control System). The aforementioned suspension and optics systems are already written in EPICS and the vacuum system is the next one to be put on that platform. EPICS is the ideal environment for LIGO control systems because it is easily placed on the existing UNIX network, allowing remote monitoring of all LIGO systems. Once on the CDS network, any LIGO personnel could view the state of the 40m vacuum system from anywhere in the world. Also, as EPICS is designed specifically for control systems, the hardware interfaces and other features are also highly compatible with the required applications.

There are three main parts to developing an EPICS application. The first is the construction of a database to link the software with the vacuum hardware via VME-based electronics. The next step is the design of a GUI (graphical user interface) that allows the operator to user a computer console to control the system. The final step is the development of state machine code that governs the transition between vacuum states and the parameters for maintaining those states.

All these steps were completed during this project and preliminary testing was done with an MV162 board. The backbone of the software has been completed, but there are still many parameters that need to be added to the system before it can be implemented.

Results

The final database includes 124 channels corresponding to 2 software variables, 78 hardware monitors (input), and 64 hardware controls (output). A summary of the database can be found in Appendix B. The actual database is simply a text file listing the various parameters detailed in the table along with some others – the expected voltage signals, the conversion to scientific units, and the alarm conditions.

The final version of the vacuum control software contains three different versions of a vacuum system GUI, which can be found in Appendix C. First, there is full manual control that allows the operator to individually operate each component of the vacuum system. This unrestricted control the vacuum system will only be available at the computer console next to the vacuum system in the 40m lab. The second level of control is state transition control, which allows the operator to tell the system to make transitions between the four main states of the system. This screen will be available anywhere in the 40m lab, accessible alongside the other main EPICS controls for the suspension and other systems. The third version is a monitor-only GUI, which will be the only interface widely available outside the 40m lab. It will allow anyone on the CDS network to view the state of each component of the vacuum system.

The state machine code includes thousands of lines of code and a summary of its function can be found in Appendix D. The bulk of the state machine code corresponds with only the state transition control GUI. The development of this code simply involved taking the established state transition procedures that were followed manually with the Labview system and translating them into state notation language, an EPICS protocol. Several safeguards were coded into the state machine, including a verification of every single vacuum component before each step and a time-delayed alarm calibrated to previously recorded pumpdowns. These safeguards warn the operator if any valve is not in its expected position and when the system takes too long to complete a specific task. The one major change to the structure of the state machine is the addition of the Temporary All Off state that can be used in the event of planned power outages or other non-catastrophic events that require shutdown.

Discussion

The EPICS-based vacuum control automates almost the entire function of the 40m vacuum system. There are four devices that still have to be operated manually for various issues of safety and convenience. The Cryopump and RGA are manually operated because of the complexity of their operation. VV1, the vent valve, is a manual valve because its accidental opening would vent the entire chamber to atmosphere. Finally, RV1, the roughing valve, and the roughing line are redundant manual connections that prevent harmful oils to flow from the roughing pumps into the chamber. The state machine notifies the operator when these devices need to be manipulated.

Also, the implementation of the Vibration-Free Pumping state has not been fully implemented during this project. The single Ion pump (IP1) on the annulus had not been able to achieve high vacuum in the past and some additional modifications will be necessary to fully utilize that pump. Also, gate valves on the rest of the ion pumps will need to be installed for safe operation during Vibration-Free Pumping.

Several very specific hardware upgrades are expected to accompany this new software. The turbopumps need to be wired so that they can be monitored and controlled manually, creating electronic monitors and switches for on/off and for standby on/off on TP2 and TP3. Along with the addition of a new side chamber, a new pneumatic valve, VABSSCO will need to be installed in the system. Also, the current BS/SC manual valve needs to be replaced with an automatic VABSSCI valve. The Cold Cathode gauge on the Mode Cleaner needs to be wired into the rest of the vacuum system and a pressure gauge needs to be installed on the Nitrogen tank. As safety measures, electronic monitors need to be installed on the roughing pump line, RGA, and High Voltage/RF switch. Also, an electronic switch for the High Voltage/RF unit needs to be installed.

In the next phase of the project, much of the hardware will need to be interfaced. A VME-based electronics module will be interfaced with the vacuum hardware using ADC’s, DAC’s, binary I/O’s, and serial port interfaces. The VME board will then be connected to a SUN workstation where the software from this project will be run.

Conclusion

The EPICS-based vacuum control system will greatly simplify the operation of the LIGO 40m prototype and will allow the researchers there to concentrate more on the detection of gravity waves and less about the operation of the 40m vacuum. The EPICS software will be implemented with the general upgrade of the 40m prototype lab, being installed on a new Sun workstation along with several new valves, a new chamber, and various optical and suspension changes, preparing the 40m prototype for the testing of various systems to be used in LIGO II and LIGO III in years to come.

Acknowledgements

I would like to thank my mentor Alan Weinstein for getting me started on this project and for helping me write this paper. Also, I would like to thank Dick Gustafson and Steve Vass in the 40m lab for teaching me everything they know about the old Labview vacuum system and about LIGO in general. Finally, I thank Jay Heefner and Lori Robison in 315 Wilson for teaching me about EPICS and about LIGO CDS.

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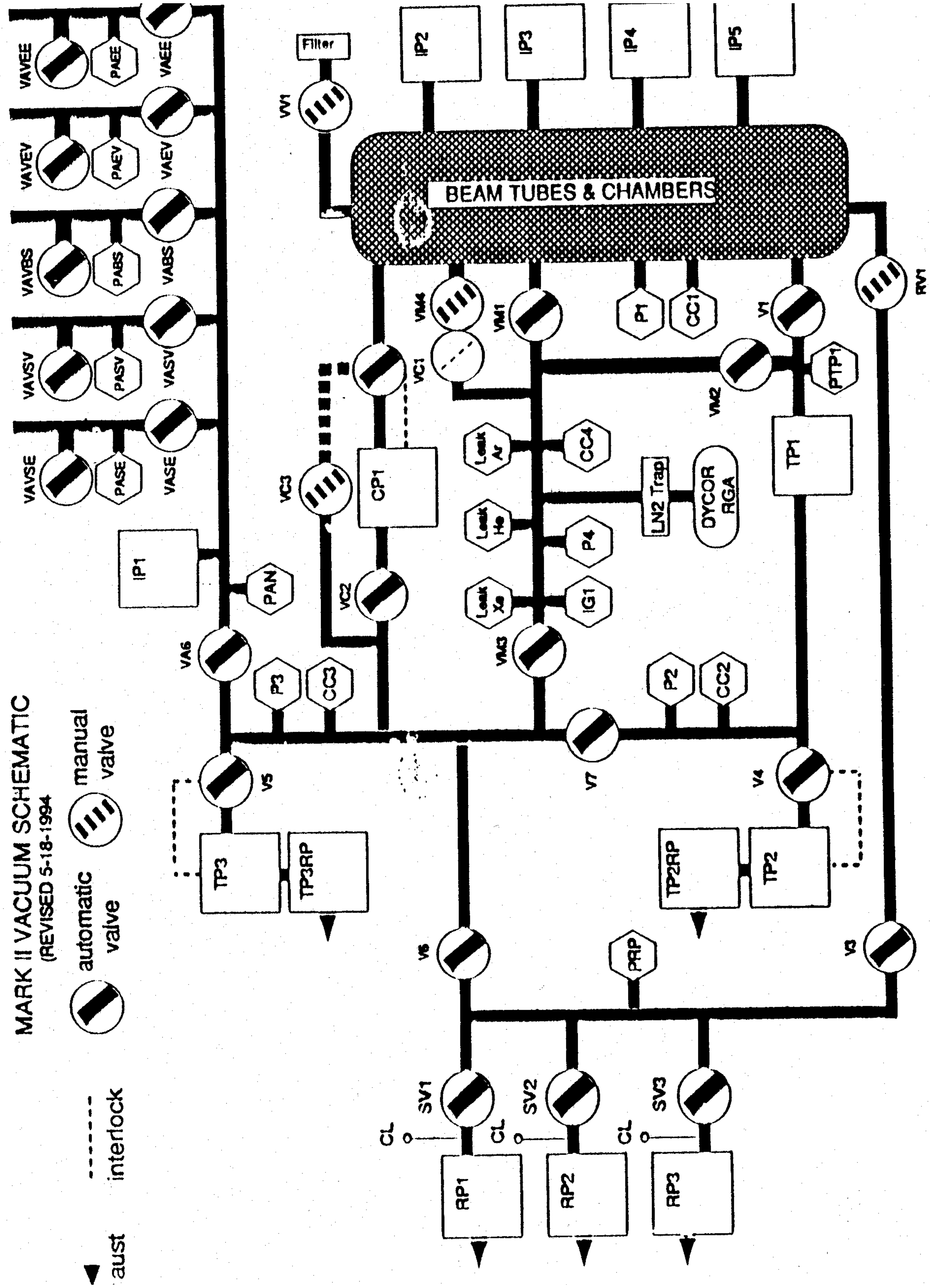
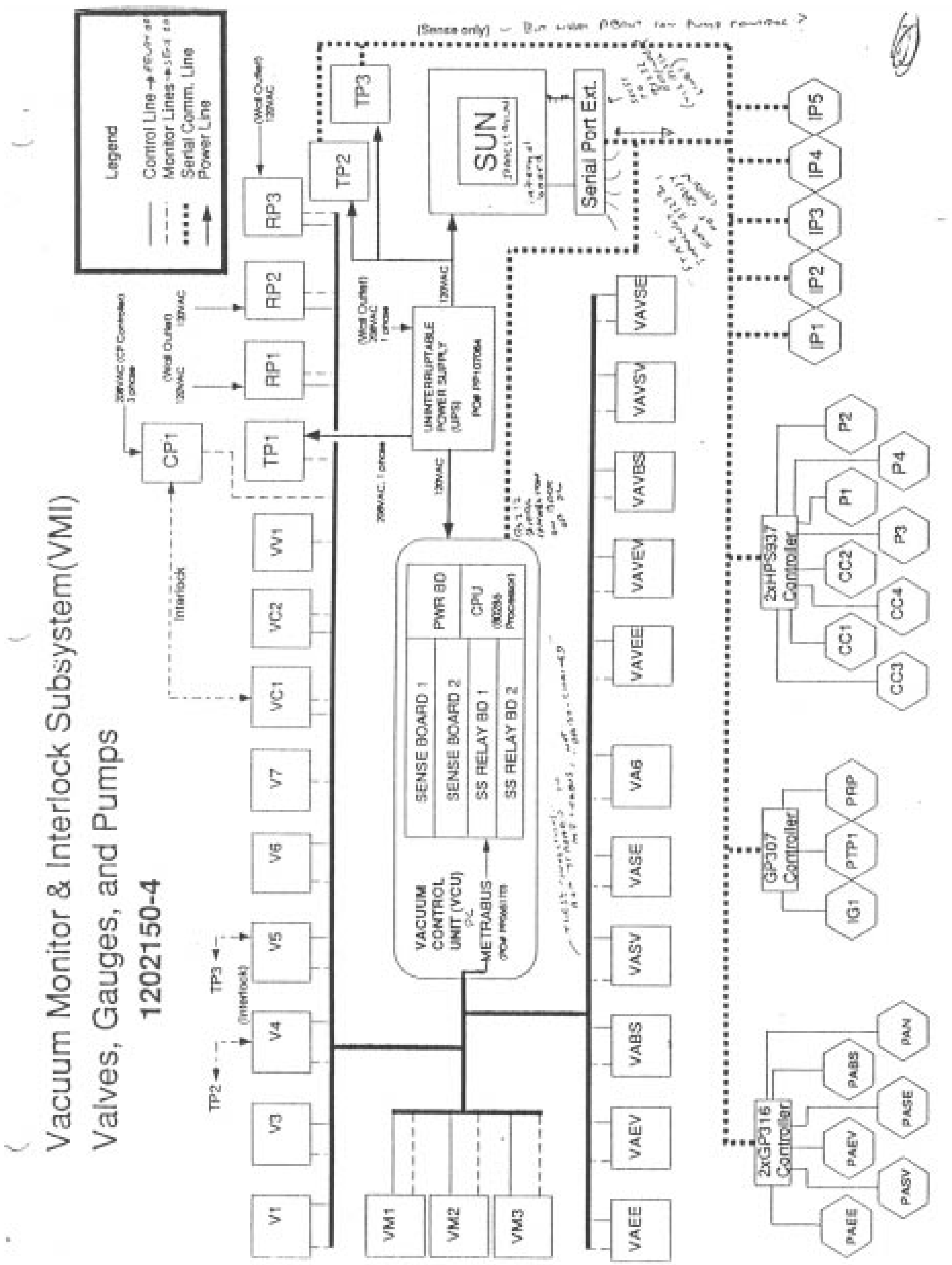
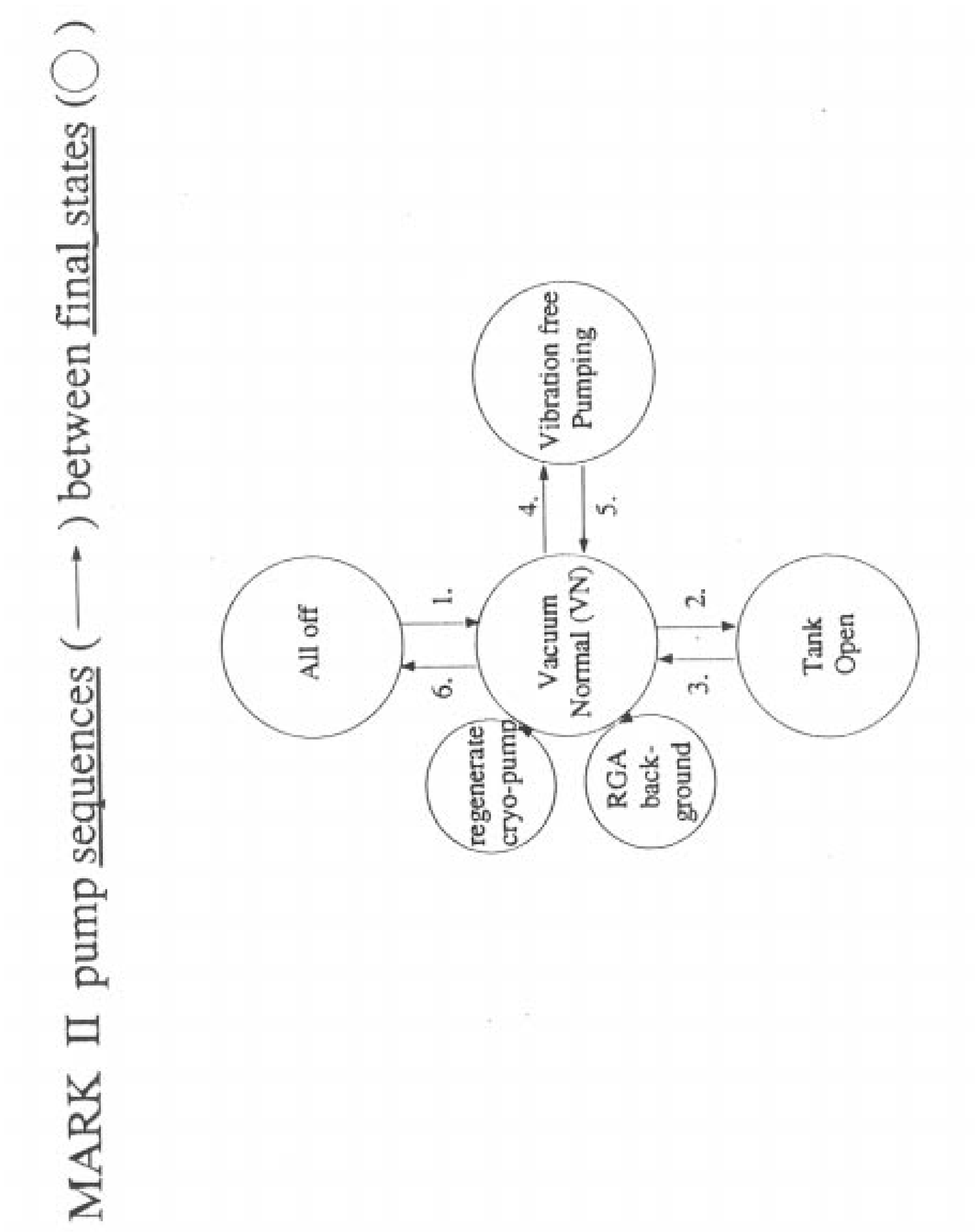
Appendix A: Current Vacuum System

Schematic




Vacuum Monitor & Interlock Subsystem(VMI)
Valves, Gauges, and Pumps
1202150-4
Legend
Control Line
Monitor Lines
Serial Comm. Line
Power Line
(Sense only)
SUN
Serial Port Ext.
UNINTERRUPTABLE POWER SUPPLY (UPS)
VACUUM CONTROL UNIT (VCU)
METRABUS
SENSE BOARD 1
SENSE BOARD 2
SS RELAY BD 1
SS RELAY BD 2
PWR BD
CPU
Interlock
(Wall Outlet)
120VAC
208VAC
V1
V3
V4
V5
V6
V7
VC1
VC2
VV1
TP1
TP2
TP3
RP1
RP2
RP3
CP1
VM1
VM2
VM3
VAEE
VAEV
VABS
VASV
VASE
VA6
VAVEE
VAVEV
VAVBS
VAVSV
VAVSE
IP1
IP2
IP3
IP4
IP5
2xHPS937 Controller
CC1
CC2
CC3
CC4
P1
P2
P3
P4
GP307 Controller
IG1
PTP1
PRP
2xGP316 Controller
PAEE
PAEV
PABS
PASE
PASV
PAN

Wiring



State Machine

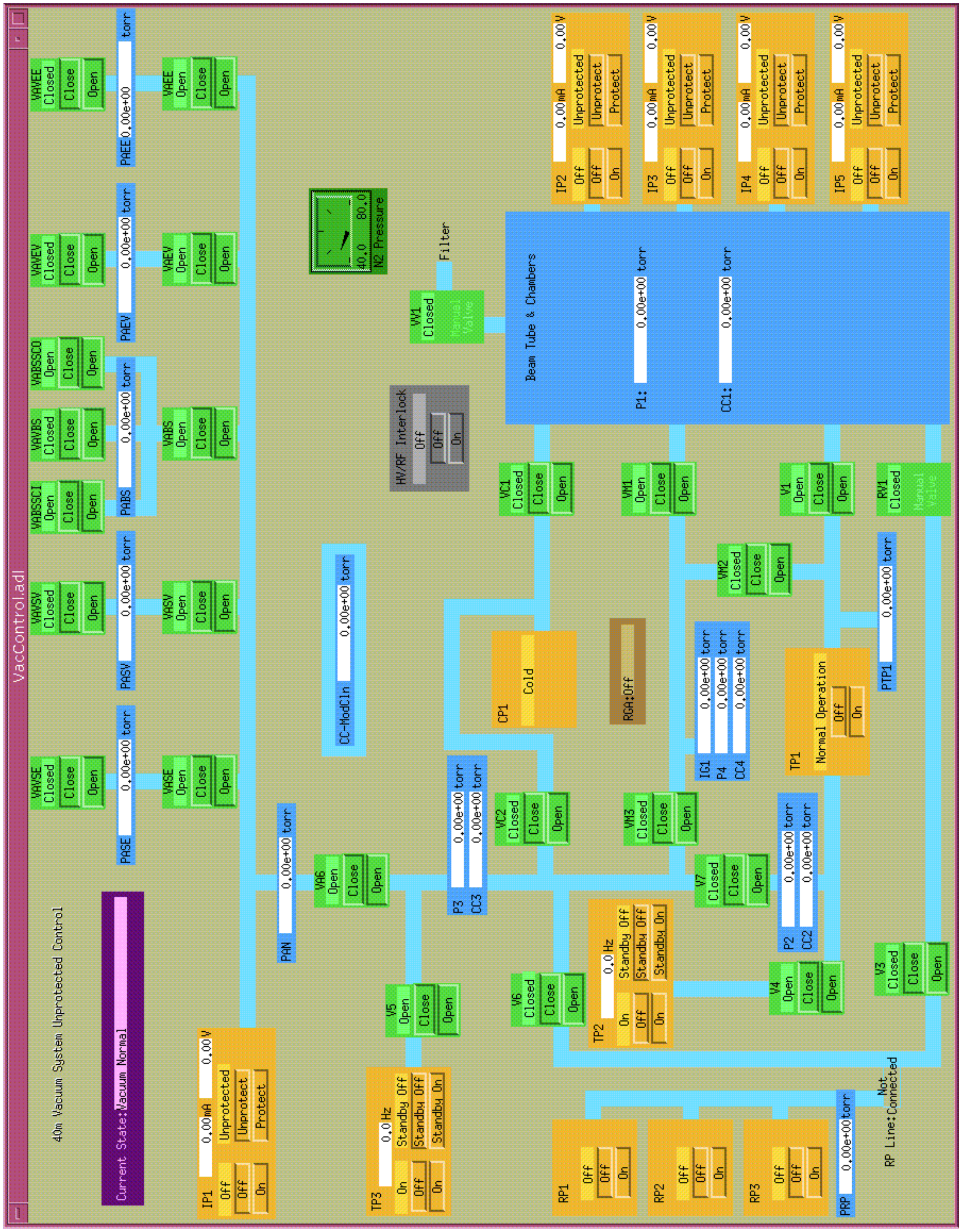
Appendix B: Summary of Database

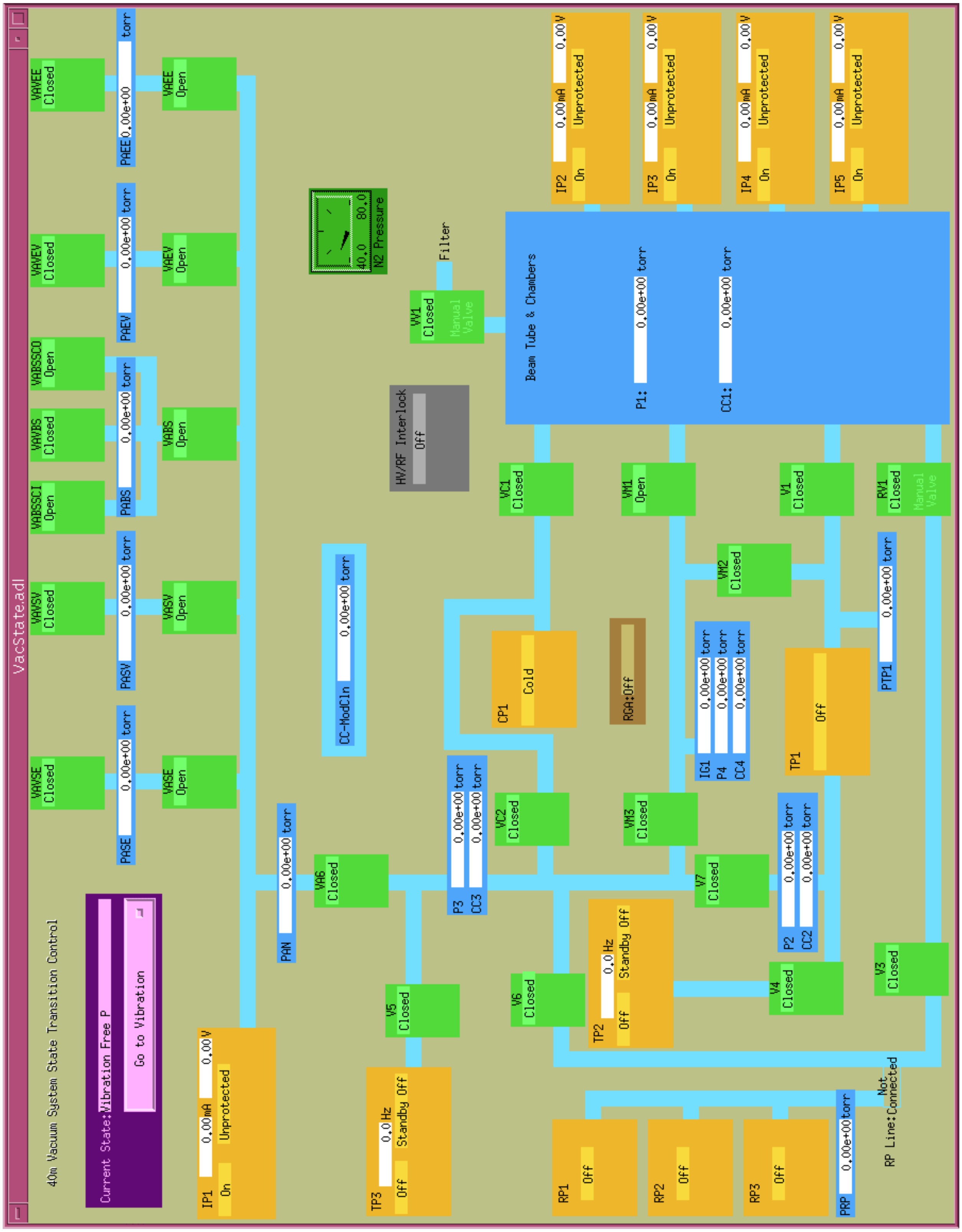
State Vector	Database Channel:	Values	State Code Variable
	*No interface		
	**No equipment		
C1:Vac-	state_mon	(soft) 012345: o,v,c,vf,trn,err	state_mon
	state_menu	(soft) 0123: off,vcNm,chOp,vbFr	state_menu
[0]	CP1_temp	0:Cold 1:Warm	CP_temp[0]
[1]	*TP1_mon	012345:off,acc,nrm,fal,lev,rot	TP_mon[0]
	*TP1_switch	0:Off 1:On	TP_switch[0]
[2]	*TP2_mon	0:Off 1:On	TP_mon[1]
	*TP2_switch	0:Off 1:On	TP_switch[1]
	*TP2_standby_mon	0:Standby Off 1:Standby On	TP_standby_mon[1]
	*TP2_standby_switch	0:Standby Off 1:Standby On	TP_standby_switch[1]
	TP2_rot	analog-Hz	TP_rot[1]
[3]	*TP3_mon	0:Off 1:On	TP_mon[2]
	*TP3_switch	0:Off 1:On	TP_switch[2]
	*TP3_standby_mon	0:Standby Off 1:Standby On	TP_standby_mon[2]
	*TP3_standby_switch	0:Standby Off 1:Standby On	TP_standby_switch[2]
	TP3_rot	analog-Hz	TP_rot[2]
[4]	**RP_line	0:not connected 1:connected	RP_line
[5]	RP1_mon	0:Off 1:On	RP_mon[0]
	RP1_switch	0:Off 1:On	RP_switch[0]
[6]	RP2_mon	0:Off 1:On	RP_mon[1]
	RP2_switch	0:Off 1:On	RP_switch[1]
[7]	RP3_mon	0:Off 1:On	RP_mon[2]
	RP3_switch	0:Off 1:On	RP_switch[2]
[8]	IP1_mon	0:Off 1:On	IP_mon[0]
	IP1_switch	0:Off 1:On	IP_switch[0]
	IP1_prot_mon	0:Unprotected 1:Protected	IP_prot_mon[0]
	IP1_prot_switch	0:Unprotect 1:Protect	IP_prot_switch[0]
	IP1_I	analog-mA	IP_I[0]
	IP1_V	analog-V	IP_V[0]
[9]	IP2_mon	0:Off 1:On	IP_mon[1]
	IP2_switch	0:Off 1:On	IP_switch[1]
	IP2_prot_mon	0:Unprotected 1:Protected	IP_prot_mon[1]
	IP2_prot_switch	0:Unprotect 1:Protect	IP_prot_switch[1]
	IP2_I	analog-mA	IP_I[1]
	IP2_V	analog-V	IP_V[1]
[10]	IP3_mon	0:Off 1:On	IP_mon[2]
	IP3_switch	0:Off 1:On	IP_switch[2]
	IP3_prot_mon	0:Unprotected 1:Protected	IP_prot_mon[2]
	IP3_prot_switch	0:Unprotect 1:Protect	IP_prot_switch[2]
	IP3_I	analog-mA	IP_I[2]
	IP3_V	analog-V	IP_V[2]
[11]	IP4_mon	0:Off 1:On	IP_mon[3]
	IP4_switch	0:Off 1:On	IP_switch[3]

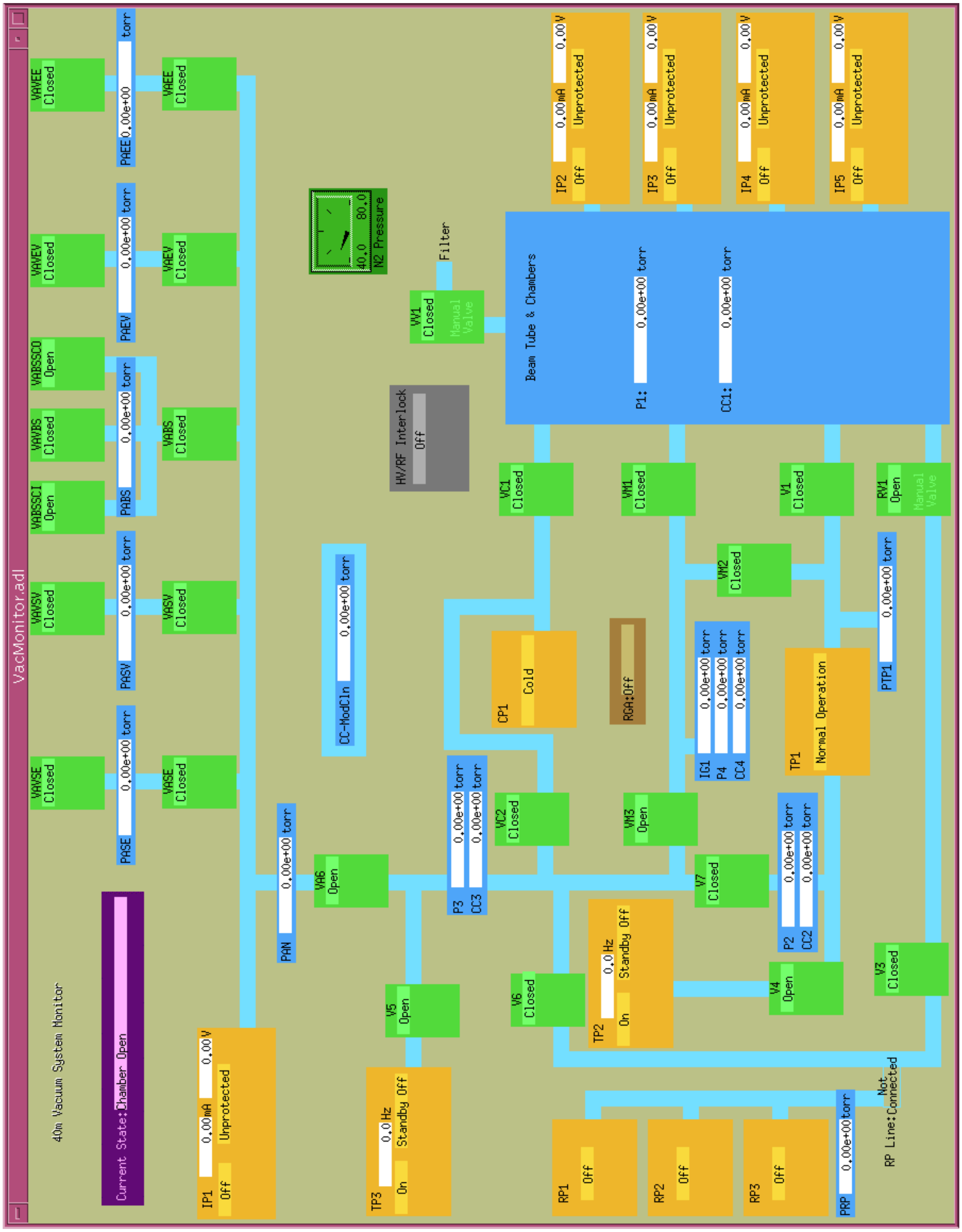
	IP4_prot_mon	0:Unprotected 1:Protected	IP_prot_mon[3]
	IP4_prot_switch	0:Unprotect 1:Protect	IP_prot_switch[3]
	IP4_I	analog-mA	IP_I[3]
	IP4_V	analog-V	IP_V[3]
[12]	IP5_mon	0:Off 1:On	IP_mon[4]
	IP5_switch	0:Off 1:On	IP_switch[4]
	IP5_prot_mon	0:Unprotected 1:Protected	IP_prot_mon[4]
	IP5_prot_switch	0:Unprotect 1:Protect	IP_prot_switch[4]
	IP5_I	analog-mA	IP_I[4]
	IP5_V	analog-V	IP_V[4]
[13]	*RGA	0:Off 1:On	RGA
[14]	V1_mon	0:Closed 1:Open	V_mon[0]
	V1_valve	0:Close 1:Open	V_valve[0]
[15]	VV1_mon	0:Closed 1:Open	V_mon[1]
[16]	V3_mon	0:Closed 1:Open	V_mon[2]
	V3_valve	0:Close 1:Open	V_valve[2]
[17]	V4_mon	0:Closed 1:Open	V_mon[3]
	V4_valve	0:Close 1:Open	V_valve[3]
[18]	V5_mon	0:Closed 1:Open	V_mon[4]
	V5_valve	0:Close 1:Open	V_valve[4]
[19]	V6_mon	0:Closed 1:Open	V_mon[5]
	V6_valve	0:Close 1:Open	V_valve[5]
[20]	V7_mon	0:Closed 1:Open	V_mon[6]
	V7_valve	0:Close 1:Open	V_valve[6]
[21]	VM1_mon	0:Closed 1:Open	VM_mon[0]
	VM1_valve	0:Close 1:Open	VM_valve[0]
[22]	VM2_mon	0:Closed 1:Open	VM_mon[1]
	VM2_valve	0:Close 1:Open	VM_valve[1]
[23]	VM3_mon	0:Closed 1:Open	VM_mon[2]
	VM3_valve	0:Close 1:Open	VM_valve[2]
[24]	VC1_mon	0:Closed 1:Open	VC_mon[0]
	VC1_valve	0:Close 1:Open	VC_valve[0]
[25]	VC2_mon	0:Closed 1:Open	VC_mon[1]
	VC2_valve	0:Close 1:Open	VC_valve[1]
[26]	VAEE_mon	0:Closed 1:Open	VA_mon[0]
	VAEE_valve	0:Close 1:Open	VA_valve[0]
[27]	VAEV_mon	0:Closed 1:Open	VA_mon[1]
	VAEV_valve	0:Close 1:Open	VA_valve[1]
[28]	VABS_mon	0:Closed 1:Open	VA_mon[2]
	VABS_valve	0:Close 1:Open	VA_valve[2]
[29]	VASV_mon	0:Closed 1:Open	VA_mon[3]
	VASV_valve	0:Close 1:Open	VA_valve[3]
[30]	VASE_mon	0:Closed 1:Open	VA_mon[4]
	VASE_valve	0:Close 1:Open	VA_valve[4]
[31]	VA6_mon	0:Closed 1:Open	VA_mon[5]
	VA6_valve	0:Close 1:Open	VA_valve[5]
[32]	VAVEE_mon	0:Closed 1:Open	VA_mon[6]
	VAVEE_valve	0:Close 1:Open	VA_valve[6]
[33]	VAVEV_mon	0:Closed 1:Open	VA_mon[7]

	VAVEV_valve	0:Close 1:Open	VA_valve[7]
[34]	VAVBS_mon	0:Closed 1:Open	VA_mon[8]
	VAVBS_valve	0:Close 1:Open	VA_valve[8]
[35]	VAVSV_mon	0:Closed 1:Open	VA_mon[9]
	VAVSV_valve	0:Close 1:Open	VA_valve[9]
[36]	VAVSE_mon	0:Closed 1:Open	VA_mon[10]
	VAVSE_valve	0:Close 1:Open	VA_valve[10]
[37]	**VABSSC_mon	0:Closed 1:Open	VA_mon[11]
	**VABSSC_valve	0:Close 1:Open	VA_valve[11]
[38]	**VABSSC2_mon	0:Closed 1:Open	VA_mon[12]
	**VABSSC2_valve	0:Close 1:Open	VA_valve[12]
[39]	RV1_mon	0:Closed 1:Open	RV_mon[0]
	P1	analog-torr	P[0]
	CC1	analog-torr	CC[0]
	P2	analog-torr	P[1]
	CC2	analog-torr	CC[1]
	P3	analog-torr	P[2]
	CC3	analog-torr	CC[2]
	P4	analog-torr	P[3]
	CC4	analog-torr	CC[3]
	*CC_ModCln	analog-torr	CCmc
	PAEE	analog-torr	PA[0]
	PAEV	analog-torr	PA[1]
	PABS	analog-torr	PA[2]
	PASV	analog-torr	PA[3]
	PASE	analog-torr	PA[4]
	PAN	analog-torr	PA[5]
	IG1	analog-torr	IG[0]
	PTP1	analog-torr	PTP[0]
	PRP	analog-torr	PRP
	**N2pres	analog-psi	N2pres
[40]	*HVRF_mon	0:Off 1:On	HVRF_mon
	*HVRF_switch	0:Off 1:On	HVRF_switch

Appendix C: GUI's




VacState.adl
40m Vacuum System State Transition Control
Current State: Vibration Free P
Go to Vibration
Beam Tube & Chambers
N2 Pressure
HV/RF Interlock
Filter
RP Line: Not Connected


VacMonitor.adl
40m Vacuum System Monitor
Current State: Chamber Open
VAVEE Closed
PAEE 0.00e+00 torr
VAEE Closed
VAVEV Closed
PAEV 0.00e+00 torr
VAEV Closed
VABSSCO Open
VAVBS Closed
PABS 0.00e+00 torr
VABS Closed
VABSSCI Open
VAVSV Closed
PASV 0.00e+00 torr
VASV Closed
VAVSE Closed
PASE 0.00e+00 torr
VASE Closed
IP1 Off 0.00mA 0.00V Unprotected
PAN 0.00e+00 torr
VA6 Open
CC-ModCln 0.00e+00 torr
40.0 80.0 N2 Pressure
HV/RF Interlock Off
VV1 Closed Manual Valve
Filter
Beam Tube & Chambers
P1: 0.00e+00 torr
CC1: 0.00e+00 torr
IP2 Off 0.00mA 0.00V Unprotected
IP3 Off 0.00mA 0.00V Unprotected
IP4 Off 0.00mA 0.00V Unprotected
IP5 Off 0.00mA 0.00V Unprotected
VC1 Closed
VM1 Closed
V1 Closed
RV1 Open Manual Valve
VM2 Closed
PTP1 0.00e+00 torr
CP1 Cold
RGA:Off
IG1 0.00e+00 torr
P4 0.00e+00 torr
CC4 0.00e+00 torr
TP1 Normal Operation
P3 0.00e+00 torr
CC3 0.00e+00 torr
VC2 Closed
VM3 Open
V7 Closed
P2 0.00e+00 torr
CC2 0.00e+00 torr
V5 Open
V6 Closed
TP2 On 0.0 Hz Standby Off
V4 Open
V3 Closed
TP3 On 0.0 Hz Standby Off
RP1 Off
RP2 Off
RP3 Off
PRP 0.00e+00 torr
RP Line: Not Connected

Appendix D: Vacuum States

All Off:
- Everything closed, everything off.

Temporary All Off: *same as All Off except chamber is assumed to maintain vacuum (10^{-3} torr)*
- Everything closed, everything off.

Vacuum Normal:
- Open: V1, V4, V5, VM1, VAEE, VAEV, VABS, VASV, VASE
- On: TP1, TP2, TP3, IP1

This state is the easiest maintainable vacuum for the system. It holds the chamber at 10^{-6} torr and the annulus at 10^{-3} torr. TP1 and TP2 in series pump on the chamber TP3 pumps on the annulus.

Chamber Open:
- Open: V4, V5, VM3, VV1
- On: TP1, TP2, TP3, IP1

This state is used when the chamber needs to be opened. The chamber is exposed to room air through VV1 while the annuluses are sealed off from outside air but still keep atmospheric pressure. This state is different from all off because the Turbopumps and Ion Pump 1 continue to operate, keeping the air volume within the vacuum system tubing at a low pressure.

Vibration-Free Pumping:
- Open: VM1, VAEE, VAEV, VABS, VASV, VASE
- On: IP1, IP2, IP3, IP4, IP5

This state is for precise measurements in high vacuum. Ion pumps are used to pump on the chamber because they create less noise. IP2-4 pump on the chamber while IP1 pumps on the annulus.

State Transitions:

All Off to Vacuum Normal:
1. When P1 > 0.001, transition is from **Temporary All Off to Vacuum Normal**. Otherwise, the operator is instructed to open the N_2 vent line and VV1. *Expected time for action: 30 + Expected time for next condition: 120; Warning time: 300*
2. When P1 rises to 25, the operator is instructed to close the N_2 line and open the lab air vent line. *30+120*; *300*
3. When P1 rises to atmospheric pressure, V7 is opened, putting P2/CC2 and P3/CC3 in the same volume. *2; 300*
4. VM3 is opened, adding the RGA and P4/CC4 to that volume. *2; 300*
5. VA6 are opened, adding the annulus volume and PAN. The operator then is instructed to open VM4 to connect this volume to the chamber. *2,30; 300*

6. TP2 is turned on. *2; 300*
7. TP2 is switched into standby. *2+120; 300*
8. When TP2 rotation accelerates to 950Hz, TP3 is turned on. *2; 300*
9. TP3 is switched into standby. *2+120+120; 300*
10. When TP3 rotation accelerates to 950Hz and the pressure between the chamber and piping to equalize (P1-PTP1<20), the operator is instructed to close VV1. *30; 300*
11. V7 is closed, cutting off P2/CC2 from the other piping. *2; 300*
12. VA6 is closed, isolating the annulus and PAN. *2; 300*
13. VM3 is closed, isolating the RGA from the piping.
14. The operator is instructed to close VM4, cutting off the RGA from the chamber, and to connect the roughing pump line. *30,30; 300*
15. RP1,2, and 3 are turned on. *2+40,2+40,2+40; 300*
16. When PRP lowers to 0.35 torr, VC2 is opened, connecting the volume of air behind CP1 to the P3/CC3 area. *2; 300*
17. V6 is opened, allowing the roughing pumps to pump out that volume of air. *2+120; 300*
18. When P3 lowers to 0.5 torr, V6 is closed, cutting off the roughing pumps from the piping. *2; 300*
19. V5 is opened, allowing TP3 to now pump on the P3/CC3 volume. *2+120; 300*
20. When CC3 lowers to 0.0001 torr, VC2 is closed, isolating the volume behind CP1. *2; 300*
21. V5 is closed, cutting off TP3 from the P3/CC3 volume. *2; 300*
22. V7 is opened, connecting the P2/CC2 volume to this volume. *2; 300*
23. V6 is opened, connecting the entire volume to the roughing pumps. *2+120; 300*
24. When P2 lowers to 0.5, V6 is closed, cutting off the roughing pumps from the piping again. *2; 300*
25. V7 is closed separating the P2/CC2 volume from the P3/CC3 volume again. *2; 300*
26. V4 is opened, allowing TP2 to pump on the P2/CC2 volume. *2; 30*
27. TP1 is then turned on, connecting PTP1 with the P2/CC2 volume. *360; 600*
28. VM3 is opened, connecting the P3/CC3 volume with the RGA. *2; 30*
29. V6 is opened, connecting P3/CC3 with the roughing pumps again. *2+???; 30+???*
30. When P3 lowers to 0.5 torr again, V6 is closed, cutting off the roughing pumps. *2; 30*
31. VM3 is closed, separating the RGA volume. *2; 30*
32. VA6 is opened, connecting the annulus line and PAN to the P3/CC3 area. *2; 30*
33. V6 is opened again, allowing the roughing pumps to pump on this new volume. *2+???; 30+???*
34. When PAN lowers to 0.5 torr, V6 is closed, cutting off the roughing pumps. *2; 30*
35. V5 is opened, allowing TP3 to pump out the annulus line. *2; 30*
36. V3 is opened. *2; 30*
37. The operator is instructed to open RV1, which allows the roughing pumps to pump directly on the chamber. *30+???; 300+???*
38. When P1 lowers to 0.5 torr, V3 is closed, cutting the roughing pumps off from the chamber. *2; 300*
39. The operator is asked to close RV1, as an extra separation. *30; 300*
40. VA6 is closed, separating the annulus line. *2; 300*
41. V7 is opened, connecting P2/CC2 and P3/CC3. *2; 300*
42. V1 is opened, allowing the turbopumps to pump out the chamber. *2; 300*
43. VM1 is opened, connecting the RGA directly to the chamber. *2; 300*

44. The roughing pumps are turned off. *2+40, 2+40, 2+40; 300*
45. When P2 lowers to 0.05 torr, the operator is instructed to disconnect the roughing pump line. *30; 300*
46. V7 is closed, separating P3/CC3 from the rest of the piping. *2; 300*
47. VA6 is opened, putting TP3 on the annulus line. *2; 300*
48. VAEE is opened, allowing pumpdown of the East End Annulus. *2+120; 300*
49. When PAN lowers to 1 torr, VAEV is opened, pumping down the next annulus. *2+120; 300*
50. When PAN gets back to 1 torr, VABS is opened, "" *2+120; 300*
51. "", VASV is opened, "" *2+120; 300*
52. "", VASE is opened, ""*2; 30*
53. The operator is instructed to turn the RGA filament on. *30; 300*
54. The system has reached the Vacuum Normal state.

Temporary All Off to Vacuum Normal:

1. TP3 is turned on. *2+120; 30+300*
2. When TP3 rotation rises to 1450Hz, TP3 standby is turned on. *2+0; 30+0*
3. When TP3 rotation rises again to 950Hz, TP2 is turned on. *2+120; 30+300*
4. When TP2 rotation rises to 1450Hz , TP2 standby is turned on. *2+0; 30+0*
5. When TP2 rotation rises again to 950Hz, V5 is opened, opening TP3 to the piping. *2; 30*
6. VA6 is opened, allowing TP3 to pump on the annulus line. *2+600; 30+1800*
7. When PAN lowers to 1, VAEE is opened, allowing the East End Annulus to be pumped out. *2+600; 30+1800*
8. When PAN lowers to 1, VAEV is opened, allowing the East Vertex Annulus to be pumped out. *2+600; 30+1800*
9. When PAN<1, VABS open, "". *2+600; 30+1800*
10. When PAN<1, VABSSCI open, "". *2+600; 30+1800*
11. When PAN<1, VABSSCO open, "". *2+600; 30+1800*
12. When PAN<1, VASV open, "". *2+600; 30+1800*
13. When PAN<1, VASE open, "". *2; 30*
14. V4 is opened, opening TP2 to the piping. *2; 30*
15. TP1 is turned on, connecting PTP1 with P2/CC2. *360; 600*
16. V1 is opened, allowing TP1 and TP2 to pump on the chamber. *2+???; 30+???*
17. When CC1<0.00001, VM1 is opened, connecting the RGA to the chamber *2; 30*
18. The operator is instructed to turn the RGA filament on. *30; 300*
19. The system has reached the Vacuum Normal state.

Vacuum Normal to Chamber Open:

1. VM1 is closed, disconnecting the RGA from the chamber. *2; 30*
2. VM3 is opened, connecting the RGA with the piping associated with P3/CC3. *2; 30*
3. V1 is closed, isloating the chamber completely. *2; 30*
4. The operator is instructed to open the N_2 valve and check various things before opening VV1. *30+2400; 300+3600*
5. When P1 rises to 25 torr, the operator is instructed to close the N_2 line and open the lab air vent valve. *30+2400; 300+3600*
6. When P1 rises to atmospheric pressure, all the VA valves are closed, cutting off the annuli from the rest of the system. *2,2,2,2; 30*
7. The first annulus is opened to lab air by opening VAVEE. *2+120; 30+300*

8. When PAEE rises to atmospheric pressure, VAVEE is closed, isolating the EE annulus at atmospheric pressure. *2; 30*
9. Then, VAVEV is open, opening the EV annulus to lab air. The same thing is done for all the annuli. *2+120; 30+300*
10. PAEV>=760, VAVEV closed. *2; 30*
11. VAVBS opened. *2+120; 30+300*
12. PABS>=760, VAVBS closed. *2; 30*
13. VASV opened. *2+120; 30+300*
14. PASV>=760, VAVSV closed. *2; 30*
15. VAVSE opened. *2+120; 30+300*
16. PASE>=760, VAVSE closed. *2; 30*
17. The system has reached the Chamber Open state.

Chamber Open to Vacuum Normal:

1. IP1 is turned off. *120; 300*
2. The operator is instructed to turn the RGA off. *30; 300*
3. VM3 is closed, isolating the RGA. *2; 30*
4. VA6 is opened, allowing TP3 to pump on the annulus line. *2; 30*
5. VAEE is opened, allowing the East End annulus to be pumped out. *2+600; 30+1800*
6. When PAN lowers to 1 torr, VAEV is opened, allowing the EV annulus to be pumped out. *2+600; 30+1800*
7. When PAN lowers to 1 torr, VABSSC is closed, isolating the side chamber annulus. *2+600; 30+1800*
8. When PAN lowers to 1 torr, VABS is opened, allowing the BS annulus to be pumped out. *2+600; 30+1800*
9. When PAN lowers to 1 torr, VABSSC is opened, allowing the side chamber annulus to be pumped out. *2+600; 30+1800*
10. When PAN lowers to 1 torr, VASV is opened, "" SV annulus "". *2+600; 30+1800*
11. When PAN lowers to 1 torr, VASE is opened, "" SE annulus "". *2+600; 30+1800*
12. When PAN lowers to 1 torr, the operator is asked to close VV1. *30; 300*
13. The operator is asked to connect the roughing pump line. *30; 300*
14. The roughing pumps are turned on. *2+40,2+40,2+40; 600*
15. When PRP lowers to 0.35 torr and N_2 pressure is greater than 60 psi, V3 is opened. *2; 30*
16. The operator is asked to open RV1. Once that is done, the roughing pumps can pump out the chamber. *30+10800; 14400*
17. When P1 lowers to 0.5 torr, V3 is closed. *2; 30*
18. The operator is asked to close RV1. *30; 300*
19. VA6 is closed, isolating the annulus line. *2; 30*
20. V7 is opened, connecting the P2/CC2 and P3/CC3 volumes. *2; 30*
21. V1 is opened, allowing all 3 turbopumps to pump out the chamber. *2; 30*
22. The roughing pumps are turned off. *2,2,2; 30*
23. The operator is instructed to disconnect the roughing line. *30+5400; 9000;*
24. When P2 lowers to 0.05 torr, V7 is closed, isolating TP3. *2; 30*
25. VA6 is opened, connecting TP3 to the annulus line. *2+7200; 30+10800*
26. When CC1 lowers to 0.00001 torr, VM1 is opened, connecting the RGA to the chamber. *2; 30*

27. The operator is instructed to turn on the RGA. *30; 300*
28. The system has reached the Vacuum Normal state.

Vacuum Normal to Vibration-Free Pumping* not really functional right now**

1. The operator is instructed to turn on the cryo-pump compressor and controller. *30; 300*
2. The operator is instructed to turn on CP1 and reset the interlock. *30; 300*
3. VC1 is opened, allowing the cryo-pump to pump out the chamber. *2+120; 300*
4. When CC1 lowers to 0.000001, the Ion Pumps (IP5-IP2) are turned on. *2+30, 2+30, 2+30, 2+30; 300*
5. When the current in IP2 lowers to 150mA, it is put into PROTECT mode. *2; 300*
6. When the current in IP3 lowers to 150mA, it is put into PROTECT mode. *2; 300*
7. When the current in IP4 lowers to 150mA, it is put into PROTECT mode. *2; 300*
8. When the current in IP5 lowers to 150mA, it is put into PROTECT mode. *2; 300*
9. V1 is closed, isolating the chamber from TP1 and TP2. *2; 300*
10. TP1 is then turned off. *2; 300*
11. V4 is closed. *2; 300*
12. TP2 is turned off. *2; 300*
13. VC1 is closed. *2; 300*
14. VC2 is opened, putting CP1, TP1, and TP3 in the same volume of air, isolated from the chamber. *2; 300*
15. The operator is then instructed to turn off CP1. *30+120; 300*
16. When the Cryo-Pump temperature reaches ‘warm’ and CC2 lowers to 0.0001 (by the pumping of TP3), VC2 is closed. *2; 300*
17. V5 is closed. *2; 300*
18. TP3 is turned off. *2; 300*
19. The system has reached the Vibration-Free pumping state.

Vibration-Free Pumping to Vacuum Normal

1. TP2 is turned on. *2; 300*
2. TP2 is switched to standby. *2+120; 300*
3. When TP2 rotation accelerates to 950Hz, TP3 is turned on. *2; 300*
4. TP3 is switched to standby. *2+120; 300*
5. When TP3 rotation accelerates to 950Hz, V4 is opened, allowing TP2 to start pumping out the tubing. *2; 300*
6. TP1 is switched on. *2; 300*
7. V5 is opened. *2; 300*
8. V1 is opened, allowing TP1 and TP3, along with TP2 to pump on the chamber. *2; 300*
9. The Ion Pumps (2-5) are then turned off. *2,2,2,2; 300*
10. The system has reached state Vacuum Normal.

Vacuum Normal to All Off

1. V1 is closed. *2; 300*
2. VC1 is closed, cutting the chamber off from the pumps. *2; 300*
3. The operator is instructed to turn off the RGA. *30; 300*
4. VM1 is closed, cutting off the RGA area. *2; 300*
5. V4 is closed. *2; 300*
6. V5 is closed, preventing TP2 and TP3 from pumping the piping. *2; 300*

7. All the VA valves are closed, cutting off the annuli from IP1. *2,2,2,2,2; 300*
8. IP1 is turned off. *2; 300*
9. TP2 and TP3 are then turned off. *2; 300*
10. The operator is instructed to switch off the cryo-pump compressor and control unit, then to turn off CP1 and close calibrated leaks. The system has reached state All Off.