MICE Operational Vacuum and Integration at RAL

**Scenario #1. Normal Operation:**

During normal operation it is desired to have the MICE cavity vacuum in the E-8 Torr range (as high as 2E-7 Torr may be possible). Operationally the shell vacuum can be in the E-5 range, but because there is some small conductance between the two vacuum volumes the lower the vacuum levels in the shell volume the better the vacuum will be in the cavities. Figure 1 is a plot of the cavity vacuum vs. conductance between the two volumes (Shell/Cavity Conductance) for various operating pressures in the shell volume.

Figure 1.

The outgassing rate for the cavity is assumed to be 2.2E-10 Torr-L/s-cm2, which is consistent with measurements made during MICE cavity tests at Fermilab’s MTA facility. This outgassing rate will improve with time under vacuum and can be further improved with ultra-high vacuum (UHV) processing. It is obvious from this plot that the smaller the conductance between the shell and cavity the easier it is to maintain the cavity in the desirable operating range. A conductance of less than 10 L/s has been chosen as the design value for this conductance. The small conductance also provides critical pumping of the non-getterable gas species. The actual gasses pumped will be mostly H2 and H2O. This will effectively cause the pressures shown in figure 1 to be slightly lower. Rough pumping of the cavities will be done with turbos through ports on the throat of the NEG pumps and only need to supply effective speeds on the order of 15 L/s per port.

For the shell vacuum, the plan is to use two large turbo-molecular roughing stations for rough down and steady state pumping. If the gas loads are consistent with what was seen during the MICE cavity tests at Fermilab’s MTA facility, effective pumping speeds of 105 L/s-m will be needed to obtain a shell vacuum of 5E-7 Torr. This would require that the effective pumping speed at the shell be greater than 300 L/s for each turbo station.

**Scenario #2. Uncontrolled Venting:**

The 201 MHz Muon Cavity has two 18-inch diameter dished beryllium windows. Beryllium is a hazardous material, so precautions must be taken to insure that if a rupture does occur personnel are not exposed to the debris. The window is 0.015 inches thick and very susceptible to fracturing due to differential pressures between the cavity and the shell and mechanical shock. For this reason care must be taken when venting the shell and cavity to atmosphere, when pumping down, or working around the window.

While the shell and cavity are under vacuum there is a risk that a catastrophic event could occur that would cause the vessel or cavity to let up suddenly. If that were to happen there could be a scenario that would cause a large enough pressure differential (~62 Torr) on opposite sides of a window to cause it to rupture. The cavity and shell communicate with each other through the by-pass line. The conductance between the cavity and shell for normal operation is less than 10 L/s. Therefore an event that causes the system to vent in an uncontrolled manner could cause the windows to rupture.

The question becomes at what deferential pressure does the integrity of the beryllium become an issue? The window is reinforced at 16.535 inches on the diameter, so the relevant stress location is at the 16.535-inch diameter. For a flat plate the maximum stress would be equal to 6M/t2, where M is equal to the radial moment at the diameter and t is equal to the plate thickness. The moment is equal to q a2/8, where a is equal to the radius and q is equal to the pressure differential. The ultimate strength of beryllium is about 65,000 psi, which would give a maximum pressure between the cavity and shell of 0.2853 psi before failure. This all assumes a flat disk though, and the actual window is dished so the 0.2853-psi (14.75 Torr) is a lower bounds for failure.

A finite element analysis (FEA) was done on the dished assembly [1] that shows the beryllium yielding at a deferential pressure of 0.76 psi on the concave side and the convex side. If we allow for a safety factor of two on ultimate strength (65,000 psi for beryllium) the FEA model shows an allowable pressure deferential of 0.6 psi (31 Torr).

The next consideration is what pressure differential is developed across the window during a rapid venting event. Since we know that the flow is choked to the shell at any pressure below 401.5 Torr the flow is constant at 11840 d2 Torr-L/s.

For compressible viscous choked flow through an orifice or nozzle the governing equations are:

Critical Pressure Ratio (Pu/Pn)Ma=1 = ((γ+1)/2)γ/(γ-1) Lafferty, Eq. 2.105

Maximum Throughput (Q) = γ0.5 (2/(γ+1))(γ+1)/(2(γ-1)) Cz Pu = G(γ) Cz Pu Lafferty, Eq. 2.106

Where: Q = Torr-L/s

γ = Specific heat ratio = 1.4 for air

Cz = (2π)0.5 Ca = (2π)0.5 (11.56 x π/4 x d2) for air

= 22.76 d2

Pu = Upstream pressure in Torr = 760 Torr

Pn = Downstream Pressure in Torr, effectively 1E-6 in this case

G(γ) = Function of γ = 0.6847

d = Diameter in cm

Therefore: (Pu/Pn)Ma=1 = 1.893

Q = 0.6847 x 760 x 22.76 x d2 = 11840 d2  Torr-L/s

If we ignore, for the moment, flow into the cavity the shell vacuum space pressure change can be caricaturized by:

Q = d(PV)/dt = VdP/dt

dP = (11840 dl 2/V) dt

Ps = (11840 dl 2 t / V) + Ps0

Where: Q = Torr-L/s

V = Volume in liters

Ps = Shell pressure (Torr)

Ps0 = Initial shell pressure (Torr)

dl = Leak diameter in cm

t = Time in seconds

The effect of the cavities pressurizing during this process would cause the shell pressure to be slightly lower with respect to time. The two cavities have a combined volume on the order of 18% of the shell volume, so the effect would be relatively small. Depending on the size of the leak diameter the shell reaches full viscous flow in a small number of milliseconds. Therefore flow into the cavity will very rapidly be choked viscous flow and be proportional to the shell pressure as long as the pressure ratio is greater than the critical ratio of 1.893. The shell to cavity throughput will then be:

Maximum Throughput (Q) = γ0.5 (2/(γ+1))(γ+1)/(2(γ-1)) Cz Pu = G(γ) Cz Pu Lafferty, Eq. 2.106

Where: Q = Torr-L/s

γ = Specific heat ratio = 1.4 for air

Cz = (2π)0.5 Ca = (2π)0.5 (11.56 x π/4 x d2) for air

= 22.76 d2

Pu = Upstream pressure in Torr = shell pressure

Pn = Downstream Pressure in Torr = cavity pressure

G(γ) = Function of γ = 0.6847

ds-c = Cavity to shell conductance diameter in cm

Therefore: (Pu/Pn)Ma=1 = 1.893

Q = 0.6847 x Pu x 22.76 x ds-c 2 = 15.58 Pu ds-c 2  Torr-L/s

Here again: Q = d(PV)/dt = VdP/dt

dP = (15.58 ((11840 dl 2 t / Vs) + Ps0) ds-c 2 / Vc) dt

Pc = (184500 dl2 ds-c 2 t2 / (2 Vs Vc)) + (15.58Ps0 ds-c2 t/Vc) + Pc0

Where: Q = Torr-L/s

Vc = Cavity volume in liters

Vs = Shell volume in liters

Pc = Cavity pressure (Torr)

Ps = Shell pressure (Torr)

Pc0 = Initial cavity pressure (Torr)

ds-c = Conductance diameter in cm

t = Time in seconds

When the shell and cavity pressures are plotted over time and the pressure differential is calculated we get a plot as seen in figure 2. Values for leak diameter and permanent shell to cavity orifice diameter are 0.5 and 0.55 cm, respectively. This gives a permanent orifice conductance of 2.75 L/s between the cavity and shell. For these calculations a shell and cavity volume is assumed to be 4329 and 397 liters, respectively. Actual values will need to be used for more accurate results.

Figure 2. Pressure vs. Time for Sudden Venting Due to 0.2” Leak.

If we allow for the leak diameter to be around 1.5 inches the plot would look like figure 3, below. As can be seen from figure 2, leaks larger than 0.2” in diameter will put the pressure differential across the windows outside the specified operating range. With a 30 Torr pressure differential as the acceptable operating limit the time it takes for the pressure differential to go from 30 to 60 Torr defines the response window available for any corrective action to be taken. Figure 4 below is a plot of the response times available for leaks of various sizes.

Figure 3. Pressure vs. Time for Sudden Venting Due to 1-½” Leak.

Figure 4. Valve Response Times Needed for Sudden Leaks.

It is hard to imagine a catastrophic event that would cause a leak larger than 1-1/2” except for the inadvertent opening of a valve. Valves larger than 1-3/8” in diameter would require response times less than one second. Fast closing valves with millisecond response times are available, but their opening times are typically in the multiple seconds range. VAT Inc. does make a butterfly series that has an opening/closing time of a little less than 1 second (0.3 s). For this reason it is best to interlock all valves, that have the potential to vent the system, in the closed position so that they cannot be opened without predetermined conditions being met. There also should to be a passive relief system in place that can react almost instantaneously to pressure differentials between shell and cavity. Circle Seal Controls, Inc. makes a “Low Pressure Check Valve” that is believed will fit this need. A “Differential Pressure Box” will need to be fabricated that will provide a passive by-pass between the shell and cavity. Under normal operating conditions the Differential Pressure Box will be inactive, but at times when the differential pressure gets too high the check valves will operate and stabilize the pressures.

**Scenario #3. Controlled Venting:**

When the system is vented in a controlled manner the beryllium windows are subjected to the danger of developing destructive differential pressures on the windows just as they are during an uncontrolled venting. For that reason it is best to vent the system from one point (see figure 6), controlling the flow to the cavities and the shell such that the pressure in each volume is always equal to each other. Venting is typically done with a 2 psi pop-off relief valve near the N2 source so the inlet to the system would be 863 Torr. At 863 Torr the critical pressure limit will be at 456 Torr, so flow will be choked until the shell and cavities reach 456 Torr. The following calculations set the diameter ratio between the cavities and the shell orifices.

Maximum Throughput (Q) = γ0.5 (2/(γ+1))(γ+1)/(2(γ-1)) Cz Pu = G(γ) Cz Pu Lafferty, Eq. 2.106

Where: Q = Torr-L/s

γ = Specific heat ratio = 1.4 for air

Cz = (2π)0.5 Ca = (2π)0.5 (11.56 x π/4 x d2) for air

= 22.76 d2

Pu = Upstream pressure in Torr = 863 Torr

Pn = Downstream Pressure in Torr, effectively 1E-6 in this case

G(γ) = Function of γ = 0.6847

d = Diameter in cm

Therefore: (Pu/Pn)Ma=1 = 1.893

Q = 0.6847 x 863 x 22.76 x d2 = 1346 d2  Torr-L/s

And: Pv = (1346 d 2 t / V) + Pv0

Where: Q = Torr-L/s

V = Volume in liters

Pv = Volume pressure (Torr)

Pv0 = Initial Volume pressure (Torr)

d= Orifice diameter in cm

t = Time in seconds

If the pressure in the shell and the cavity are to remain equal then:

(1346 ds 2 t / Vs) + Ps0 = (1346 dc 2 t / Vc) + Pc0

ds 2 / Vs = dc 2 / Vc

ds 2 / dc 2 = Vs / Vs

ds/dc= (Vs / Vc)0.5

ds/dc= (4329 / 397)0.5 = 3.302

ds= 3.302 dc

Therefore if the cavity orifice is 0.55 cm the orifice to the shell should be 1.82 cm. Figure 5 below is the pressure verses time curve for controlled venting.

Figure 5. Controlled Venting

**Scenario #4. Controlled Pumpdown:**

For pumpdown if we want the pressure in the cavity and the shell to be equal through the viscous region the ratios of the shell/cavity pumping speeds and the shell/cavity volumes must be equal (Ss/Sc = Vs/Vc = 10.9). Ss and Sc are the effective pumping speeds at the entrance to the respective volumes. It should be noted that the cavity pumping speed is for each cavity and the shell pumping speed is the total pumping speed on the shell. In this case 30 and 2.75 L/s are the shell and cavity speeds, respectively. Therefore the pumping speeds at each location would be 15 L/s for the shell and 2.75 L/s for the cavity. The pumping speeds for roughing pumps and turbos are, in general, variable and dependent on the pressure at which they are pumping. Therefore care must be taken in the selection of the pumps to use so that the ratio is maintained.

The general equation for pumpdown is:

P(t) = (P0 – (Qin/S) exp(-(S/V)t)) + Qin/S Lafferty, Eq. 9.7

Where: P = Volume pressure (Torr)

P0 = Initial volume pressure (Torr)

Qin = Gas flow from outgassing (Torr-L/s)

V = Volume (L)

Figure 6 below shows the pumpdown curves for the shell and cavities assuming pumping speeds of 30 and 2.75 L/s, respectively. Volumes are assumed to be 4329 and 397 liters for the shell and cavity, respectively. Gas loads are assumed to be 4.26E-4 and 9.84E-6 Torr-L/s for the shell and cavity, respectively. These values are estimates, so more accurate numbers need to be used. Once the system is comfortably in the E-5 Torr range the larger turbos on the shell can be turned on and the valve to the cavity can be opened. With all the turbos on the system should comfortably reach the low E-7 Torr range and the NEG’s can be activated.

Figure 6. Controlled Pumpdown

**Vacuum Integration Plan:**

There are three ways to look at controlling the vacuum process. The first is to automate everything so that all valves and pumps are electronically controlled through some programmable logic. The second would be that everything is manually controlled and each operation would need to follow a procedural check list. The third option would be some combination of the first two. Creating a program that samples component status and then opens/closes valves and turns on/off pumps is a fairly straight forward technology. Problems arise when there is an electronics or mechanical failure with no human oversite. The problem with manual operation is the human interaction. There is always human error and a limited reaction time.

Because of the high magnetic field all electronic components and some mechanical components within the field may not function properly, if at all. Critical gauges will need to be positioned outside the strong magnetic field through long a conductance, thereby reducing their range of operation. Mechanical pumps that need to operate when the field is on will also need to be positioned outside the strong magnetic field.

Figure 7. Mice Vacuum Schematic Layout.



Table 1. Venting Procedure.

|  |  |
| --- | --- |
|  | Check Box |
| 1) Valves GV-1A, GV-1B, GV-2A, GV-2B, GV-3A, GV-3B, GV-4A, GV-4B, & PnV-5 in closed position. |  |
| 2) 1/4" Hand Angle Valve (vent valve) in closed position. |  |
| 3) Turn off getters (NEG) pump controller and allow getter to cool down. |  |
| 4) Turn off Turbos on GV-4A, GV-4B, GV-1A & GV-1B. |  |
| 5) After Turbos have spooled down turn off rough pumps. |  |
| 6) Connect dry N2 bottle with pressure relief (1 to 2 psi) to vent port and open N2 flow slowly until relief valve activates. |  |
| 7) Open PnV-5. |  |
| 8) Slowly open 1/4" Hand Angle Valve (vent port). |  |
| 9) Allow N2 to Flow until vessel and cavity are vented. Pressure relief will pop-off at this point. |  |
| 10) Shut off N2 flow and close vent port. |  |
| 11) The shell and cavity will be under slight positive pressure at this point. Cracking the vent port slightly will relieve this pressure. Close vent port after relieving pressure. |  |

Table 2. Pumpdown Procedure.

|  |  |
| --- | --- |
|  | Check Box |
| 1) Valves GV-2A, GV-2B, GV-4A, GV-4B, & PnV-5 in closed position. |  |
| 2) Valves GV-1A, GV-1B, GV-3A, & GV-3B in open position. |  |
| 3) Connect rough pumps to 150 L/s turbo stations A & B. Rough pumps must have anti-suck back valves. |  |
| 4) Turn on rough pumps at turbo stations A & B. |  |
| 5) When Pirani gauges indicate low pressure (~1E-2 Torr) start 150 L/s turbo stations A & B. |  |
| 6) Start Large Turbo Stations A & B. |  |
| 7) When Large Turbo Station gauges indicate low pressure (<1E-5 Torr) open GV-4 A&B. |  |
| 8) When cavity high vacuum gauges indicate low pressure (<1E-5 Torr) open GV-2 A&B. |  |

Table 3. NEG Activation Procedure.

|  |  |
| --- | --- |
|  | Check Box |
| 1) With cavities under vacuum in the 1E-7 Torr range and all turbos operating. |  |
| 2) Connect the NEG Pump Controller V1.1 cable to the CapaciTor D3500 NEG. |  |
| 3) Set potentiometer on the NEG Pump Controller V1.1 to the 8.4 setting. |  |
| 4) Set thermoregulation to ON on the NEG Pump Controller V1.1. |  |
| 5) Set temperature stop value to 550 C on the NEG Pump Controller V1.1. |  |
| 6) Set over temperature alarm value to 560 C on the NEG Pump Controller V1.1. |  |
| 7) Start the NEG Pump Controller V1.1. |  |
| 8) Allow the NEG Pump Controller V1.1 to ramp up to 550 C and hold at that value for 45 minutes. |  |
| 9) Turn off the NEG Pump Controller V1.1 and allow to cool to below 200 C. |  |
| 10) Set over temperature alarm value to 560 C on the NEG Pump Controller V1.1. |  |
| 11) Start the NEG Pump Controller V1.1. |  |
| 12) Allow the NEG Pump Controller V1.1 to ramp up to 550 C and hold at that value for 45 minutes. |  |
| 13) Set potentiometer on the NEG Pump Controller V1.1 to the 2.7 setting. |  |
| 14) Set thermoregulation to ON on the NEG Pump Controller V1.1. |  |
| 15) Set temperature stop value to 200 C on the NEG Pump Controller V1.1. |  |
| 16) Set over temperature alarm value to 210 C on the NEG Pump Controller V1.1. |  |
| 17) Start the NEG Pump Controller V1.1. |  |
| 18) Close GV-1 A&B, GV-2 A&B, and GV-3 A&B when cavity tree ion gauge reads less than 5E-8 Torr. |  |
|  |  |

Table 4. Valve Status

|  |  |  |  |
| --- | --- | --- | --- |
| Valve | Operational Condition | Status | Conditional Requirements |
|  |  |  |  |
| GV-1 A&B | Operation | Closed |  |
|  | Venting | Closed |  |
|  | Pumpdown | Open |  |
|  | Power Out | Closed |  |
|  |  |  |  |
| GV-2 A&B | Operation | Closed |  |
|  | Venting | Closed |  |
|  | Pumpdown | Closed from atmosphere to 1E-5 Torr and operation |  |
|  |  | Open < 1E-5 Torr |  |
|  |  |  |  |
| GV-3 A&B | Operation | Closed |  |
|  | Venting | Closed |  |
|  | Pumpdown | Open |  |
|  |  |  |  |
| GV-4 A&B | Operation | Open |  |
|  | Venting | Closed |  |
|  | Pumpdown | Closed from atmosphere to 1E-5 Torr |  |
|  |  | Open < 1E-5 |  |
|  | Power Out | Closed |  |
|  |  |  |  |
| PnV-5 | Operation | Closed |  |
|  | Venting | Open |  |
|  | Pumpdown | Closed |  |
|  | Power Out | Closed |  |

Figure 8. MICE Vacuum By-Pass Line Schematic.

