CC CRYOSTAT VACUUM PUMPING EFFICIENCY

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APPROVED:

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INTRODUCTION: This report calculates the effect of the conductances of the pumping lines on the pumping speeds of the vacuum pumps being used to pump the inner vessel, and annular space, vacuum tight during the CC Cryostat testing.

EQUIPMENT AND LINES USED (annular space):

A small blower equipped vacuum pumping cart (Leybold-Heraeus Trivac® A Rotary Vane Pump model #D30a [27cfm] & Ruvac® Single Stage Roots Pump model #WSU150 [100CFM]), is to be used to pump the annular space of the CC Cryostat. The Roots pump kicks in at 10 mm Hg pressure. (SEE REF. 4)

The connecting line from the vacuum pumping cart to the CC Cryostat is to be flex hose with 4.14 cm. I.D. (KF40), and approximate length of 381 cm. A KF40 90° angle valve (open) is assumed to be part of the final setup.

EQUIPMENT AND LINES USED (inner vessel):

The vacuum pump under consideration for pumping the inner vessel is the Stokes 1721-S model. The Microvac® pump on the Stokes operates at a pumping speed of 150 cfm. The Stokes has a blower which operates at 2200 R.P.M. providing a 1600 CFM displacement. The blower cuts in at 10 mm Hg pressure. (SEE REF. 5)

The connecting line from the Stokes to the CC Cryostat is to be 4 inch O.D. tubing, approximately 842 cm. in length and 9.83 cm. inside diameter. A long sweep 90° elbow, as well as a tee used as an elbow entering a run are assumed to be a part of the final setup.

CALCULATIONS:

The conductance of a cylindrical tube assuming viscous laminar flow of air at 20°C is given by:

$$C = [(0.182)*(D^4)*(P_{ave})] / (L)$$

Where:

C is the conductance (l/s).

D is the tube diameter (cm).

L is the tube length (cm).

P_{ave} is the average pressure in the tube (μ).

Note: when $D*P_{ave} \geq 500 \mu\text{-Cm}$ then the calculation is accurate to within 10%. (SEE REF. 6)

The effective pumping speed of the system (s_{sys} (l/s)) is given by:

$$S_{sys} = [(C_{tot})*(S_p)] / (C_{tot} + S_p)$$

Where: C_{tot} is the sum total of all the line conductances. (l/s)

S_p is the intrinsic pumping speed of the vacuum pump. (l/s)

Note: The total of i number of conductances occurring in series is given by $[1/c_{series} = \sum 1/c_i]$, while the total of i number of conductances in parallel is given by $[1/c_{parallel} = \sum c_i]$. (SEE REF. 6)

CALCULATIONS (con't):

The pumpdown time (t (sec)) is given by:

$$t = - (v_{sys} / s_{sys}) * \ln(p_{n+1} / p_n)$$

Derived from:

$$p_{n+1} = p_n * e^{(-t/\tau)}$$

where:

v_{sys} is the volume of the enclosure to be pumped. (liters)

s_{sys} is the effective pumping speed of the pump with connecting lines, etc... (l/s)

p_{n+1} is the current pressure. (μ)

p_n is the original pressure. (μ)

Note: (v_{sys}/s_{sys}) is equal to a time constant (τ), that varies with pressure in the viscous laminar flow region. (SEE REF. 4)

METHODS OF CALCULATION:

Effective pumping speeds were calculated for various values of pressure via the above stated formulas (see calculations). Conductances of valves, elbows, and tees were calculated with the help of ref. 1, and the volumes of the inner vessel and annular space were calculated with the aid of ref. 2. The major results of these calculations follow. The attached graphs show the effective pumping speed vs. pressure, as well as the pressure vs. pumpdown time for both the inner vessel pumpdown and the annular space pumpdown. Many intervals of pressure were chosen in order to give a complete picture of the effects on the pumping speed, and pumpdown time.

RESULTS:

<u>RESULTS:</u>	ANNULAR SPACE		INNER VESSEL	
	=====			
PRESSURE	t (hrs)	s_{sys} (l/s)	t (hrs)	s_{sys}(l/s)
(μ)				
=====	=====	=====	=====	=====
760,000	0.00	12.53	0.00	70.23
100,000	0.31	12.51	0.37	70.19
10,000	0.69	11.80	0.79	69.79
BLOWERS ARE IN EFFECT BELOW 10,000 μ PRESSURE				
5,000	0.72	39.30	0.80	658.80
1,000	0.83	24.00	0.84	444.80
100	1.44	4.40	1.03	95.60

=====

ACTUAL ANNULAR SPACE PUMPDOWN DATA:

During the course of this report the annular space was pumped effectively by a similar setup to the one described. The following data was collected, and is exhibited in an attached overlay graph:

<u>PRESSURE (μ)</u>	<u>RUNNING PUMPDOWN TIME (HRS)</u>
760,000	0
11,000	1.33
2,400	1.50
1,200	1.58
950	1.83
710	2.36
580	14.83
150	15.42
18	16.83

CONCLUSION:

It is clear that the actual pumping of the annular space closely matches the theoretical predictions, except for a period of time while a leak went undetected (see graph). The pumping arrangement chosen for the job pumped the annular space to 1000 μ in about 1.75 hours; the predicted time was 0.83 hours. This variation may be due to a slightly different final setup, as well as inadequacies inherent in the pump itself. The annular space was found to be tight with a rate of rise of only 1 μ per minute at 18 μ .

ACTUAL INNER VESSEL PUMPDOWN:

During the course of this report the inner vessel was pumped effectively by a similar setup to the one described. The following data was collected, and is exhibited in an attached overlay graph:

<u>PRESSURE (μ)</u>	<u>RUNNING PUMPDOWN TIME (HRS)</u>
760,000	0
217,578	.33
20,721	.83
1,000	1.00
160	1.17
90	1.33

CONCLUSION:

It is clear that the actual pumping of the inner vessel closely matches the theoretical predictions. (see graph). The pumping arrangement chosen for the job pumped the inner vessel to 1000 μ in about 1.00 hour whereas the predicted time was 0.84 hours. Again, this variance is most likely due to inefficiencies in the Stokes 1721-S pump and a slightly different final arrangement of the pumping network.

FINAL CONCLUSION:

An important rule of thumb is that the effective pumping speed be close to the intrinsic pump speed in the region of interest for the best efficiency. With an infinite conductance, these quantities become equal. In the case of the annular space pumpdown, the effective pumping speed is within approximately 15% of the intrinsic pump speed for pressures down to 6000μ , and at that point, the conductance effects slow the system down and provide a 49% difference at 1000μ . To improve these numbers, the line length must be shortened, or even better, the line diameter increased. As far as pumpdown time is concerned, the actual pumpdown was completed in a reasonable amount of time, and would have been even better if the pumping system did not lag due to a leak and its repair time.

The inner vessel pumpdown shows a pumpdown time near 1 hour to reach 100μ pressure. The effective pumping speed matches to within 10% of the intrinsic pump speed to 6000μ , and then the conductance effects become more important and provide a 41% difference at 1000μ . The actual pumpdown was completed in a reasonable amount of time which demonstrates that the pump used was in fact adequate for this application.

REFERENCES

1. McAdams, William H., "Heat Transmission", McGraw-Hill Book Co., New York, 1954. (see attached page 161)
2. Trotter, G.R, "D-Zero central calorimeter and end caps parameter layout-elevation", drawing number 3740.220-ME-222256, rev. J.
3. Brandt, J. , "D-Zero detector central calorimeter cryostat view A-A/South End Elevation", drawing number 3740.214-ME-223235, sht. 2 /8, rev. A.
4. Leybold-Heraeus Inc., "Product and Vacuum Technology Reference Book", 1985-1986.
5. Pennwalt Corp., "Stokes® Multi-Stage High-Capacity Vacuum Pumps Series MB and Series 1700", Bulletin 536A.
6. Condon, E. U. and Hugh Odishaw (ed.), "Handbook of Physics", chpt. 6 McGraw-Hill Book Co., New York, 1958.

Pressure (u)	S_{sys} (%)	T (sec)	Δt (sec)	t (sec)
760,000	12.53	553.9	—	0.0
100,000	12.51	554.8	1125.2	1125.2
10,000	11.80	588.1	1354.2	2479.4
9000	42.33	163.9	17.3	2496.7
8000	41.83	165.9	19.54	2516.24
7000	41.2	168.4	22.5	2538.74
6000	40.4	171.8	26.48	2565.22
5000	39.3	176.6	32.19	2597.41
4000	37.8	183.5	40.9	2638.31
3000	35.5	195.2	56.2	2694.51
2000	31.7	218.7	88.7	2783.2
1000	24.0	289.2	200.0	2983.21
750	20.6	336.1	96.7	3079.91
500	16.1	430.1	174.4	3254.31
250	9.7	711.8	493.4	3747.71
100	4.4	1577.3	1445.3	5193.01
50	2.3	3017.4	2091.5	7284.51
25	1.2	5783.3	4008.7	11293.21
10	.48	14458.3	13248.0	24541.21

Recd pump
K2K5 on →

INNER VESSEL PUMPDOWN CHART DATA

Pressure (u)	S_{sys} (%)	T (sec)	Δt (sec)	t (sec)
760,000	70.23	653.5	—	0.0
100,000	70.19	653.9	1326.3	1326.3
10,000	69.79	657.7	1514.3	2840.6
9000	615.95	65.95	6.9	2847.5
8000	693.16	66.22	7.8	2855.3
7000	682.2	67.28	8.98	2864.3
6000	672.2	68.28	10.52	2874.8
5000	658.8	69.68	12.70	2887.5
4000	639.5	71.77	16.01	2903.5
3000	609.9	75.26	21.65	2925.2
2000	558.1	82.24	33.35	2958.5
1000	444.8	103.18	71.52	3030.0
750	391.8	117.15	33.70	3063.7
500	316.4	145.07	58.82	3122.5
250	200.6	228.8	158.62	3281.1
100	95.6	480.1	439.91	3721.0
50	51.0	900.0	623.83	4344.83
25	26.4	1738.6	1205.1	5549.9
10	10.8	4250.0	3894.2	9444.13

Blower
K2K5 on →

ANNULAR SPACE PUMPING SPEED VS. PRESSURE

INNER VESSEL PUMPING SPEED VS. PRESSURE

Inner Vessel
Intrinsic Pump Speed

(Ref. 5)

Annular Space
Intrinsic pump speed

(REF 4)

Performance Curves

Data from "10/7/87 ANNULAR SPACE PUMPDOWN TIME DATA"

Data from "10/9/87 INNER VESSEL PUMPDOWN TIME DATA"

Effective Pumping Speed for Pumping Annular Space

Equipment: TRIVAL[®] A Rotary Vane Pump (D30 A) (26.8 cfm)
w/ RuVAL[®] WS150 Single Stage Root pump (100 cfm) or (46.8 $\frac{L}{s}$)

Lines: Port to Be used is THE Diffusion Pump Port (N14V)

$$[L] = 150'' \times \frac{2.54 \text{ cm}}{1''} = [381 \text{ cm}]$$

$$[I.D.] = 1\frac{5}{8}'' \times \frac{2.54 \text{ cm}}{1''} = [4.14 \text{ cm}]$$

Connections, valves, elbows, etc...: (using Ref. 1)

① KF40 Angle Valve $\Rightarrow [I.D.] = 1\frac{5}{8}'' = [4.14 \text{ cm}]$
(OPEN)

$$L_e/D = 170 \Rightarrow [L_e] = 170 \times 4.14 = [703.8 \text{ cm}]$$

Total conductances:

CASE 1 $\Rightarrow \bar{P} = 100 \mu$

$$C_{\text{line}} = \frac{(0.182)(4.14)^4(100)}{381} = 14.0 \frac{L}{s}$$

$$C_{\text{valve}} = \frac{(0.182)(4.14)^4(100)}{703.8} = 7.6 \frac{L}{s}$$

$$[C_{\text{TOT}}] = \frac{1}{\frac{1}{14} + \frac{1}{7.6}} = [4.9 \frac{L}{s}]$$

CASE 2 $\Rightarrow \bar{P} = 1000 \mu$

$$C_{\text{line, case 2}} = C_{\text{line, case 1}} \times 10 = 140 \frac{L}{s}$$

$$C_{\text{valve}} = 76 \frac{L}{s}$$

$$[C_{\text{TOT}}] = \frac{1}{\frac{1}{140} + \frac{1}{76}} = [49.3 \frac{L}{s}]$$

Effective Pumping Speeds:

CASE 1

$$[S_{\text{sys}}] = \frac{C_{\text{TOT}} S_p}{(C_{\text{TOT}} + S_p)}$$

$$= \frac{(4.9)(46.8)}{(4.9 + 46.8)} = [4.4 \frac{L}{s}]$$

CASE 2

$$[S_{\text{sys}}] = \frac{(49.3)(46.8)}{(49.3 + 46.8)}$$

$$= [24.0 \frac{L}{s}]$$

CC CRYPSTAT → Annular space Volume (see Ref. 2)

$$\text{outer volume} \approx \pi \left(\frac{204 - 2(\frac{5}{8})}{2} \right)^2 (109) - \pi \left(\frac{193.5}{2} \right)^2 (109)$$

$$= 3,519,152.6 - 3,205,371.1$$

$$= \boxed{313,781.5 \text{ in}^3}$$

$$\text{inner volume} \approx \pi \left(\frac{64.375}{2} \right)^2 (109) - \pi \left(\frac{59.844 + 2(\frac{1}{4})}{2} \right)^2 (109)$$

$$= 354,773.24 - 311,734.28$$

$$= \boxed{43,038.96 \text{ in}^3}$$

$$\text{Head Volume} \approx \pi \left(\frac{204 - 2(\frac{5}{8})}{2} \right)^2 (1.125) - \pi \left(\frac{59.844}{2} \right)^2 (1.125)$$

$$= 36,321.53 - 3164.34$$

$$= \boxed{33,157.19 \text{ in}^3}$$

$$\boxed{\text{TOTAL Annular space volume}} \approx \text{outer volume} + \text{inner volume} + (2) \text{Head volume}$$

$$= 313,781.5 + 43,039 + 2(33,157.19)$$

$$= 423,134.88 \approx \boxed{423,135 \text{ in}^3}$$

$$\text{or } 423,135 \text{ in}^3 \left(\frac{1.64 \times 10^{-5} \text{ m}^3}{1 \text{ in}^3} \right) \left(\frac{1 \text{ L}}{1 \times 10^{-3} \text{ m}^3} \right) = \boxed{6,940 \text{ Liters}}$$

Effective Pumping Speed For Pumping Inner Vessel

Equipment: Stokes 1721-S (1600 CFM) (748.8 $\frac{1}{s}$)

Lines: Length = 1.5 * Altitude to Port

Port used is High Voltage Port (N2P)
Altitude $\approx 221''$. (See Ref. 3)

$$[L] = 221'' \times 1.5 = 331.5' \times \frac{2.54 \text{ cm}}{1''} = \boxed{842 \text{ cm}}$$

Diameter $\Rightarrow 4''$ O.D. Tubing, wall thickness = 65 mills

$$[I.D.] = \left[4'' \times \frac{2.54 \text{ cm}}{1''} \right] - \left[2(65 \text{ mills}) \times \frac{1 \text{ inch}}{1000 \text{ mills}} \times \frac{2.54 \text{ cm}}{1''} \right]$$

$$10.16 \text{ cm} - .33 \text{ cm} = \boxed{9.83 \text{ cm}}$$

Connections, valves, elbows, etc.: (using Ref. 1)

① 90° Elbow, long sweep. $\Rightarrow \frac{L_e}{D} = 20 \Rightarrow [L_e] = 20(9.86) = \boxed{177.2 \text{ cm}}$

② Tee (used as elbow, entering Run) $\Rightarrow \frac{L_e}{D} = 60 \Rightarrow [L_e] = 60(9.86) = \boxed{531.6 \text{ cm}}$

Total conductances:

CASE 1 $\Rightarrow \bar{P} = 100 \mu$

$$C_{\text{Line}} = \frac{(182)(9.83)^4(100)}{842} = 201.8 \frac{1}{s}$$

$$C_{90^\circ \text{ elbow}} = \frac{(182)(9.83)^4(100)}{177.2} = 959.0 \frac{1}{s}$$

$$C_{\text{tee}} = \frac{(182)(9.83)^4(100)}{531.6} = 319.7 \frac{1}{s}$$

$$[C_{\text{TOT}}] = \frac{1}{\frac{1}{201.8} + \frac{1}{959.0} + \frac{1}{319.7}} = \boxed{109.6 \frac{1}{s}}$$

CASE 2 $\Rightarrow \bar{P} = 1000 \mu$

$$C_{\text{Line}} = C_{\text{Line Case 1}} \div 10 = 20.18 \frac{1}{s}$$

$$C_{90^\circ \text{ elbow}} = 95.90 \frac{1}{s}$$

$$C_{\text{tee}} = 31.97 \frac{1}{s}$$

$$C_{\text{TOT}} = \frac{1}{\frac{1}{20.18} + \frac{1}{95.90} + \frac{1}{31.97}}$$

$$[C_{\text{TOT}}] = \boxed{1095.8 \frac{1}{s}}$$

Effective pumping speeds for stokes

CASE 1 $\Rightarrow \bar{p} = 100 \mu$

$$\boxed{S_{sys}} = \frac{S_p C_{TOT}}{S_p + C_{TOT}}$$

$$= \frac{(748.8)(109.6)}{(748.8) + (109.6)}$$

$$= \boxed{95.6 \text{ } \frac{1}{s}}$$

CASE 2 $\Rightarrow \bar{p} = 1000 \mu$

$$S_{sys} = \frac{(748.8)(1095.8)}{(748.8) + (1095.8)}$$

$$= \boxed{448 \frac{1}{s}}$$

CC CRYOSTAT → Inner Vessel Volume (see Ref 2)

$$\checkmark \boxed{\text{Inner Vessel Volume}} \approx \pi \left(\frac{193.5 - 2(\frac{5}{8})}{2} \right)^2 (109) - \pi \left(\frac{64.375 + 2(\frac{3}{8})}{2} \right)^2 (109)$$

$$= 3,164,091.8 - 363,087.96$$

$$= \boxed{2,801,003.8 \text{ in}^3}$$

$$2801003.8 \text{ in}^3 * \frac{1.64 \times 10^{-5} \text{ m}^3}{\text{in}^3} * \frac{1 \text{ Liter}}{1 \times 10^{-3} \text{ m}^3} =$$

$$= \boxed{4.59 \times 10^4 \text{ Liters}}$$

CALCULATION OF PumpDown TIMES FOR Annular space & THE INNER VESSEL

use: $P_{n+1} = P_n e^{-t/\tau_n}$

where: τ_n is a time constant that depends on the pressure. $\tau_n = \frac{V_{sys}}{S_{sys}}$

t = pumpdown time

P_n = Previous pressure

P_{n+1} = current pressure

Solving for t :

$$\ln\left(\frac{P_{n+1}}{P_n}\right) = -t/\tau_n$$

$$t = -(\tau_n) \ln\left(\frac{P_{n+1}}{P_n}\right)$$

$$\text{So } t = -\left(\frac{V_{sys}}{S_{sys}(P)}\right) \ln\left(\frac{P_{n+1}}{P_n}\right)$$

* Note That For Both pumping systems,
The S_{sys} changes DRASTICALLY at 10,000 m
Because A Blower Kicks on.

Ref 1

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FLOW OF FLUIDS

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(total angle of divergence may be calculated by inte- (6-2c), and (6-8a). Where t, no simple treatment will

ation of Eqs. (6-9b), (6-10),

te inside the straight horizontal of cross section). The air enters and leaves at 180°F. The tubes Calculate (a) the pressure drop se over-all pressure drop between cross sections twice those of the

f air, expressed as lb/(ft)(sec), is 1/2 is (3/2)(2), the values of DG/μ responding values of f are 0.0077

0075. The hydraulic radius r_h = air is 29.0, that is, 29 lb of air occu- measure.

1 cu ft/lb

entially normal barometric pressure,

1 cu ft/lb

0.1 cu ft/lb

By Eq. (6-9b)

$$\frac{0.0075(19)(2)^2(20.1)}{(64.4)(1/2)}$$

3 pounds force/sq ft

$$\frac{1}{1.2 \text{ ft/sec}^2} \left(\frac{1}{62.3 \text{ lb/ft}^3} \right) \left(\frac{12 \text{ in.}}{1 \text{ ft}} \right) = 0.630 \text{ in. water}$$

ent of the net heat input [Eqs. (6-4a)

$$Q = (0.24)(500 - 180) + \frac{(32.2)^2 - (48.2)^2}{(778)(64.4)} = 76.8 - 0.0257 \text{ Btu/lb}$$

b. From Fig. 6-13, $K_e = 0.3$, whence by Eq. (6-10)

$$p_0 - p_1 = \frac{V_1^2 - V_2^2}{2g_s \rho_{avg}} + \frac{K_e V_1^2}{2g_s \rho_{avg}} = \frac{(48.2)^2 - (32.2)^2}{(64.4)(24.1)} + \frac{(0.3)(48.2)^2}{(64.4)(24.1)} = 1.12 + 0.45 = 1.57 \text{ pounds force/sq ft}$$

By Eq. (6-11)

$$p_1 - p_2 = \frac{V_2^2 - V_3^2}{2g_s \rho_{avg}} + \frac{(V_2 - V_3)^2}{2g_s \rho_{avg}} = \frac{(16.1)^2 - (32.2)^2}{(64.4)(16.1)} + \frac{(32.2 - 16.1)^2}{(64.4)(16.1)} = -0.75 + 0.25 = -0.5 \text{ pound force/sq ft}$$

SUMMARY

Differences	Pounds force Square foot	Inches of water
$p_0 - p_1 = 1.12 + 0.45$	+1.57	+0.301
$p_1 - p_2 = -0.99 + 4.27$	+3.28	+0.630
$p_2 - p_3 = -0.75 + 0.25$	-0.50	-0.096
$p_0 - p_3$	4.35	0.835

Since 1 atm is equivalent to a pressure of $(14.69)(144) = 2115$ pounds force/sq ft, little error was made in neglecting the change in p in calculating v_2 . Assuming 500 air tubes, the volumetric rate of flow at the exit would be $(500)(3.14)(1)/(144)(32.2) = 351$ cu ft/sec at normal pressure. With the fan at the exit, the power theoretically required would be $(351)(4.35/550) = 2.77$ hp.

Fittings. These are allowed for by assigning a fictitious or equivalent length L_e of straight pipe to the existing straight pipe and using the sum $L_e + L$, in Eq. (6-2d) for turbulent flow. For DG/μ above 2100 to 3000,

TABLE 6-4. L_e/D RATIOS FOR SCREWED FITTINGS, VALVES, ETC., TURBULENT FLOW ONLY*

Fitting	L_e/D	Fitting	L_e/D
45-deg elbows.....	15	Tee (used as elbow entering branch).....	90
90-deg elbows, standard radius..	32	Couplings, unions.....	Negligible
90-deg elbows, medium radius.....	20	Gate valves, open.....	7*
90-deg elbows, long sweep.....	20	Gate valves, one-fourth closed..	40*
90-deg square elbows.....	60	Gate valves, one-half closed.....	200*
180-deg close return bends.....	75	Gate valves, three-fourths closed	800*
180-deg medium-radius return bends.....	50	Globe valves, open.....	300*
Tee (used as elbow, entering run).....	60	Angle valves, open.....	170*

* Perry,¹² p. 290.

[†] Rough estimate; values depend on construction of valve.