DØ SOLENOID UPGRADE PROJECT

Vacuum pumping calculations
for the DØ Solenoid

D-ZERO ENGINEERING NOTE # 3823.111- EN-348

August 2, 1993

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RD/DØ Mech.
INTRODUCTION

This engineering note documents the calculations done to determine the vacuum pumping speed for the D-Zero solenoid. The raw calculations are attached. A summary of the results are listed below.

RESULTS

The vacuum pumping speed of the solenoid is determined by the conductance of the pumping path. At higher pressure ranges during initial pumpdown, the conductances will be rather high. Calculations were not done for the transient pumpdown period, only the steady state type pumping situation. The pressure is assumed to be on the order of 10E-7 torr. This is the free molecular flow regime based on Knudsen number. This pressure regime is also where the pumping speed would be least.

The conductances were calculated based on pumping helium gas at a temperature of 300 Kelvin. The total conductance of the pumping path from the solenoid to the inlet of the turbomolecular pump is 11.8 L/s. The effective pumping speed of a 1000 L/s turbo pump attached to this pumping path is 11.7 L/s.

The minimum required pumping speed for design purposes was set at 4.3 L/s. This value was arrived at by assuming a warm leak size (10E-8 atm-cc/sec) was not detected during fabrication of the solenoid. It is then assumed that the leak leaks cold liquid helium into the vacuum space. With this leak rate, a 4.3 L/s pumping speed would be able to maintain a 2 x 10E-7 torr pressure in the solenoid vacuum jacket. The solenoid would be able to be operated with this small leak with continuous pumping.

CONCLUSION

The effective pumping speed calculated for the solenoid and chimney is greater than that required to keep the solenoid operational even if a small liquid helium leak was leaking into the insulating vacuum space.
EXPLANATION OF ATTACHED CALCULATIONS

Several sets of calculations are attached. They are in chronological order with the most recent calculations first. Each set is described below.

*Calculations dated 8/2/93 thru 8/10/93, Pages 1 thru 5:

These calculations summarize the conductances of the pumping path as described in the August 11, 1993 version of the Design Report. These calculations heavily reference previous calculations. These calculations are the source for the effective pumping speed $= 11.7 \text{ L/s}$.

*Calculations dated 5/17/93, Pages 1 thru 6:

These calculations were done before/during the time it was determined that the turbomolecular pump had to be moved. The calculations do contain the latest conductance value calculated for the obround section however. Pages 5 and 6 show the 'new' decision to move the turbo under the control dewar. These calculations also allude to the plan to expand the vacuum jacket from 8" pipe to 10" to get higher pumping speeds.

*Calculations dated 11/13/92, Pages 1 thru 3:

These calculations were done to determine the conductance through the obround chimney section. They determined that the obround should be increased from 3" x 6 3/4" to 3" x 7" to get a much improved conductance.

*Calculations dated 10/7/92 thru 10/13/92, Pages 1 thru 12:

These calculations were the first I did to try to determine whether to use a separate dedicated pumping line or to use the cryo utility transfer line vacuum space. At this date, it was not clear whether the chimney could run vertically from the solenoid or not. The calculations on page 11 conclude that the minimum design pumping speed is 4.3 L/s.
Vacuum Pumping Calculations

These calculations build upon earlier calculations.

Reference 5/17/93 (6 pages), 11/13/92 (3 pages), 10/7/92 (12 pages)

Calculations by me.

I use the old calculations as a source for some numbers, proof of flow regime - free molecular and format of conductance calculations.

Conductances of Pumping Path

The pumping path has been broken down into 9 parts as itemized on page 2.

Previously it has been shown (10/7/92, page 3) that for the 2 x 10^-5 torr pressure range, the Knudsen x is very high meaning we are in a free molecular flow regime.

All conductances will be calculated for pumping on helium gas at 300K. I neglect pumping inside LN2 shields.

Part 1 Elbow into-obround

This will be modeled as a 90° elbow.

The hydraulic diameter of the tube part is:

\[ D_h = D_0 - D_1 = (4.75 \text{ in.} - 3.50 \text{ in.}) = 1.25 \text{ in.} \]

For obround: \( D_h = 1.49 \text{ in.} \) [Ref. 5/17/93, page 2]

Use 90° elbow, i.d. = 1.375 in. \( \approx 2.5 \text{ in.} \)

\[ C = 141 \frac{\text{L}}{\text{S}} \text{ from TK solver} \]

\[ C = \left( \frac{2.8 \times 10}{7 \text{torr}} \right)^{1/2} D^3 \]
VACUUM PUMPING CALCULATIONS

PART 1  OBROUND

\[ C_{\text{obround}} = 22.9 \text{ L/s} \]

\[ \text{REF. 5/17/93 PAGE 2 CALC.} \]

PART 2  ELBOW

THE GEOMETRY OF THIS ELBOW IS NOT CLEARLY DEFINED.

MODEL AS A 90° ELBOW.

\[ D_{\text{M,obround}} = 1.49 \]

\[ D_{\text{D,8x6}} = D_2 - D_1 = 8.329 - 6.625 = 1.704 \text{ in.} \]

USE 1.D. = 1.60 in. \quad \& \quad r = 4.25 \text{ in.}

\[ C = 131 \text{ L/s from TK SOLVER} \]

PART 3  8" PIPE WITH 6" PIPE LN2 SHIELD

\[ C = 113 \text{ L/s} \]

\[ \text{REF. 5/17/93 PAGE 2 CALC.} \]

PART 4  ELBOW

USE 1.D. = 1.704 in. \quad r = 8 \text{ in} \quad \{\text{SHORT RADIUS ELBOW, PIPE FITTER\'}}\n
\[ C = 84 \text{ L/s from TK SOLVER} \]

PART 5  SHORT PIECE OF 9 X 6" PIPE SHIELD

\[ L \approx 0.5 \text{ m} \]

\[ C = 568 \text{ L/s from TK SOLVER} \]

PART 6  10" PIPE VAC. JACKET, 6" PIPE SHIELD

\[ L \approx 3.5 \text{ m} \]

\[ a = 10.585 \text{ in.} \quad b = 6.625 \text{ in.} \]

\[ \frac{b}{a} = 0.61 \]

\[ k = 1.207 \quad \text{REF. BALKAN \'}} \]

\[ \text{TABLE 8.1 \'}} \]

\[ C = 561 \text{ L/s from TK SOLVER} \]

PART 7  TEE TO PUMP

LINE TO PUMP WILL BE 6" PIPE, SCH. 10S.

\[ \text{L eff = L axial + 1.33 D} \]

\[ \text{REF. VACUUM EQUIPMENT \& TECHNIQUES, 1949} \]

\[ \text{KIND OF ATOM (I.D. OF 6" PIPE SCH. 10) GUTHRIE \\& WAKERLING} \]

\[ \text{L eff = 0.5 m + 1.33 (6.35\text{"})(0.0254\text{m})} \]

\[ = 0.715 \text{ m} \]

\[ C = \frac{3.5}{0.715} (561 \text{ L/s}) = 2750 \text{ L/s} \]
*PART 9* 6" PIPE TO PUMP

\[ L \approx 54_{m} \quad \frac{L}{D} = \frac{54}{6.357} \approx 8.5 \times 30 \text{ } \text{short tube.} \]

There will be a vacuum value in between.

\[ C_{\text{vacuum value}} = 9.154 \text{ } L/s \]

Ref. ANS calculations, pg. 9 of SOCC detector solenoid design note #117. kept in wh11x RD/MECH. support group.

For first half \( L \approx 27_{m} = 0.686 \text{ } m \)

\[ C = 1541 \text{ } L/s \text{ from tk solver using barenw eq. 8.1} \]

\[ C_{\text{part 9}} = \left( \frac{1}{1541} + \frac{1}{9154} + \frac{1}{1541} \right)^{-1} = 712 \text{ } L/s. \]

Total conductance, solenoid to pump:

\[ C_{\text{total}} = \left( \frac{1}{141} + \frac{1}{229} + \frac{1}{131} + \frac{1}{131} + \frac{1}{84} + \frac{1}{568} + \frac{1}{561} + \frac{1}{2750} + \frac{1}{712} \right)^{-1} \]

\[ = 11.8 \text{ } L/s \]

If we use 1000 \( L/s \) TURBO

\[ S_{\text{eff}} = \left( \frac{1}{11.8} + \frac{1}{1000} \right)^{-1} = 11.7 \text{ } L/s \]
CALCULATE CONDUCTANCES AND PUMPING SPEED FOR SOLENOID AND CONTROL DEWAR.

Pumping Path | Conductance (Free Molar Regime)
--- | ---
1. Obround chimney | 22.9 l/s
2. N-S chimney run | 113.0
3. Lower incline | 482.5
4. Vertical tube | 231.5
5. Upper incline | 52.4

SECTION 1
MODEL AS 2 RECTANGLES + 2 TUBES.

i) Rectangles measured along sides of LN2 shield to be: 0.40625" x 4.50" x L = 9.5 ft = 2.75 m
Use TK solver: A/B = 0.903 => K = 1.46 Table 8.1 of Baren, case 5

\[ C = 4.93 \text{ l/s}, T = \frac{300}{4.93} \text{ K} \]

ii) Space at end
\[ f = 1.3125", A = \frac{\pi D^2}{4} \]

**Vacuum Pumping**

\[ H = 1.3125 - \frac{\sqrt{3}}{2} = 1.03125 \]
\[ D = 2.625'' \]

\[ A = \frac{\pi}{4} \left(2.625''\right)^2 \times 1.36481 = 1.974 \text{ in}^2 \]

\[ \Theta = \sin^{-1} \left( \frac{\sqrt{3}}{2} \times 1.3125'' \right) = 12.3736^\circ \]

\[ \Phi = 180 - 20 = 155.25^\circ = 2.709 \text{ radians} \]

\[ S = \Phi D = (1.3125')(2.709 \text{ radians}) = 3.556 \text{ in.} \]

\[ C = 2 \times 1.3125 \cos \Theta - 2 \times 0.30625'(3') = 1.7515 \text{ in.} \]

\[ P = \text{Perimeter} = S + C = 3.556 + 1.752 \omega = 5.31 \text{ in.} \]

\[ D_h = 4 \times \Gamma_4 = 4 \times \frac{A}{\Phi} = \frac{1.974 \text{ in}^2}{5.31 \text{ in.}} = 1.49 \text{ in.} \]

**Use TR Solver:** Long tube \( \frac{H}{D} > 30 \), **Free Molec.**

\[ C_{\text{free}} = 0.50 \% \text{ for one end} \]

\[ C_{\text{total}} = 2 \times C_{\text{rect.}} + 2 \times C_{\text{end}} = 2 \times \left( 4.93 \% \right) + 2 \times \left( 6.50 \% \right) \]

\[ = 22.9 \% \]

**2** N-S CHIMNEY RUN

Model as annulus, \( D_1 = 8.329 \text{ in.} \), \( D_2 = 6.625 \text{ in.} \)

\( L = 9.2 \text{ ft} \approx 2.75 \text{ m} \)

\( \frac{D_2}{D_1} = 0.795 \Rightarrow k = 1.35 \)

<table>
<thead>
<tr>
<th>( T )</th>
<th>( \text{He} )</th>
<th>( \text{N}_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 K</td>
<td>113.0</td>
<td>42.7</td>
</tr>
<tr>
<td>80 K</td>
<td>58.9</td>
<td>22.1</td>
</tr>
</tbody>
</table>
3. LOWER INCLINE
   ANNUlus  L = 1.9 ft = 0.6 m  
            T   He   N₂
   300 k   482.5  182.4
   80 k    249.2  194.2

4. VERTICAL TUBE.
   FREE TO CHOOSE PIPE SIZE
   TRY 6" PIPE, SCH. 10S  →  i.d. = 6.357"
   L = 15 ft. to 20 ft. = 4.5 m
   L/ \( \delta = \frac{20 \text{ ft} \times 12 \text{ in}/1 \text{ ft}}{6.357} \) = 37.8 > 30 : LONG TUBE

   T   He   N₂
   300 k  231.5  87.5 l/s
   80 k   119.5  45.2

5. UPPER INCLINE  L ≈ 20 ft, 6 m
   T   He   N₂
   300  52.4  19.8
   80   27.1  10.2

MISCELLANEOUS:
   [PWR ANS
   10/2/93
   SCO CSHCS.]
   [SCO DESIG
   NOTE #117]

   6" SCHE. 10S LONG RADIUS EL BOW, 90°
   C = 2374 l/s  300 k, He GAS

   4" SCHE. 10S LONG RADIUS 90° C = 1100 l/s
Total Conductances,

A) Pump to Solenoid

\[ C_{\text{Total}} = \left[ \frac{1}{22.4} + \frac{1}{113.0} + \frac{1}{462.5} + \frac{1}{231.5} + \frac{1}{1000} \right]^{-1} \]

\[ = 15.9 \ \text{liters} \ \text{sec}^{-1} \]

at 300K, He

B) Pump to Control Dewar

\[ C_{\text{Total}} = \left[ \frac{1}{52.4} + \frac{1}{231.5} + \frac{2}{1000} \right]^{-1} = 39.4 \ \text{liters} \ \text{sec}^{-1} \]

Selection of Pump Speed

\[ S_{\text{eff}} = \left[ \frac{1}{C_{\text{Total}}} + \frac{1}{S_{\text{nom}}} \right]^{-1} \]

<table>
<thead>
<tr>
<th>Turbo Pump Speed</th>
<th>S_{\text{eff}} Solenoid</th>
<th>S_{\text{eff}} Control Dewar</th>
</tr>
</thead>
<tbody>
<tr>
<td>135 \text{ lit/sec}</td>
<td>14.2</td>
<td>30.5</td>
</tr>
<tr>
<td>380 \text{ lit/sec}</td>
<td>15.3</td>
<td>35.7</td>
</tr>
<tr>
<td>440</td>
<td>15.3 (5)</td>
<td>36.2</td>
</tr>
<tr>
<td>620</td>
<td>15.5</td>
<td>37.0</td>
</tr>
<tr>
<td>1000</td>
<td>15.6 (5)</td>
<td>37.9</td>
</tr>
</tbody>
</table>

If we pump on Solenoid thru chimney up to control dewar location 

\[ C_{\text{Total}} = 12.9 \ \text{liters} \ \text{sec}^{-1} \]

Can't put turbo in muon truss due to stray magnetic field. Ruggi says B = 200 gauss. Will move turbo onto lower platform.
CONDUCTANCE OF 3):
WHAT IF LN\textsubscript{2} SHIELD IS REDUCED TO 5\textquotedblright O.D.? 

\[
\frac{b/a}{m} = \frac{4.875}{8.329} = 0.5853 \quad K = 1.20 \\
L = 12 \text{ ft} = 3.7 \text{ m} \quad C = 267.7 \frac{\text{l/s}}{300 \text{K}} \quad \text{He gas}
\]

SECTION 2): \( L = 2.75 \); 5\textquotedblright O.D. SHIELD 

\( C = 356.4 \frac{\text{l/s}}{300 \text{K}} \)  

SECTION 4): 6\text{"} PIPE, \( L = 1 \text{ m} \)

SHORT TUBE CONDUCTANCE: 
\( C = 1142.8 \frac{\text{l/s}}{300 \text{K}} \)  

TOTAL CONDUCTANCES:

A) PUMP TO SOLENOID 

\[
C_{\text{TOTAL}} = \left[ \frac{1}{22.9} + \frac{1}{356.4} + \frac{1}{267.7} + \frac{1}{1142.8} + \frac{4000}{1000} \right]^{-1} = 18.1(5) \frac{\text{l/s}}{300 \text{K}}
\]

B) PUMP TO CONTROL DEWAR \((13 = 21)\)

\[
C_{\text{TOTAL}} = \left[ \frac{1}{356.4} + \frac{1}{1142.8} + \frac{3000}{1000} \right]^{-1} = 149.7 \frac{\text{l/s}}{300 \text{K}}
\]
**VACUUM PUMPING FOR SOLENOID.**

**PRELIMINARY SELECTION OF PUMP.**

<table>
<thead>
<tr>
<th>Turbo Pump Speed</th>
<th>Seff Solenoid</th>
<th>Seff Control Dewar</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 L/s</td>
<td>17.3</td>
<td>107.4</td>
</tr>
<tr>
<td>440</td>
<td>17.4</td>
<td>111.7</td>
</tr>
<tr>
<td>620</td>
<td>17.6</td>
<td>120.6</td>
</tr>
<tr>
<td>1000 L/s</td>
<td>17.8</td>
<td>130.2</td>
</tr>
</tbody>
</table>

Go with 1000 L/s Turbo Pump.
Lembold Model TMP1000 would be suitable.

Decided against reducing shield size to 5" O.D.
Might be too cramped.
Will plan on expanding vacuum jacket
to 10" pipe for incline portion of chimney,
will need to redo calcs.
Conductance Calculations / Pumping Speed.

Estimate conductance of 3" x 6 3/4" obround section

\[
\text{Flow Area} = \frac{\pi \left(2.625\text{ in.}\right)^2 + (3.75\text{ in.})(2.625\text{ in.}) - (2\text{ in.})(4.5\text{ in.})}{4} = 6.2556\text{ in.}^2
\]

\[
\text{Wetted Perimeter} = \pi (2.625\text{ in.}) + 2(3.75\text{ in.}) + 2(4.5\text{ in.} + 2\text{ in.}) = 28.747\text{ in.}
\]

\[
R_h = \frac{A}{P} = \frac{6.2556\text{ in.}^2}{28.747\text{ in.}} = 0.2176\text{ in.}
\]

\[
D_h = 4R_h = 0.87\text{ in.}
\]

For an annulus:

\[
\Gamma_h = \frac{\frac{1}{4} \left[ \pi D_1^2 - \pi D_2^2 \right]}{\pi D_1 + \pi D_2}
\]

\[
\Gamma_h = \frac{1}{4} (D_1 - D_2) \quad \text{or} \quad D_h = D_1 - D_2
\]

The conductance Eqn for annulus is:

\[
C = \left[ \frac{\frac{1}{8} c R_h t K}{18 M} \right]^{1/2} \left( D_1 - D_2 \right) \left( D_1 + D_2 \right) \frac{(D_1 - D_2)^2}{L^2 + 4/3 (D_1 - D_2)}
\]

Try to get an equivalent \( D_1 \) & \( D_2 \)

\[
\pi D_1 = \pi (2.625) + 2(3.75) \quad \Rightarrow \quad D_1 = 5.0123\text{ in.}
\]

\[
\pi D_2 = 13\text{ in.} \quad \Rightarrow \quad D_2 = 4.138\text{ in.}
\]

\[
D_1 - D_2 = 5.0123\text{ in.} - 4.138\text{ in.} = 0.8743\text{ in.}
\]

\[
L = 7\text{ ft.} = 2.134\text{ m} \quad \Rightarrow \quad D_2/D_1 = 0.825569 \quad \Rightarrow \quad K = 1.385
\]

Using TK SOLVER:

\[
C = 24.2 \text{ L/s} \quad \text{FREE MOLECULAR REGIME}
\]
Try to model as parallel paths of 4 rectangles.

**Rectangle 1:**
- \(a = 0.3125 \text{ in.}\)
- \(b = 4.5 \text{ in.}\)
- \(a/b = 0.0694 \Rightarrow K = 1.5122\)

**Rectangle 2:**
- \(a = 0.9375 \text{ in.}\)
- \(b = 2.0 \text{ in.}\)
- \(a/b = 0.4623 \Rightarrow K = 1.1518\)

\[L = 2.134 \text{ in.}, \quad T = 300K, \quad M = 4 \text{ molecular flow regime}\]

\[C = \left(\frac{32g_0R_uT}{9T^2M}\right)^{\frac{1}{2}} \frac{a^2b^3K}{(a+b)L + 2/3ab}\]

Use the solver already set up.

\[C_{\text{Rect. 1}} = 3.97 \frac{\text{in.}^2}{\text{s}}\]
\[C_{\text{Rect. 2}} = 8.78 \frac{\text{in.}^2}{\text{s}}\]
\[C_{\text{Total}} = 2C_{\text{Rect. 1}} + 2C_{\text{Rect. 2}} = 25.68 \frac{\text{in.}^2}{\text{s}} = 25.7 \frac{\text{in.}^2}{\text{s}}\]

The annulus model and this rectangular model agree within 6%.

Check conductance of annulus in rest of transfer line.
Assume 3/4 SCH. 10 vacuum jacket & 0.25 in. O.D. radiation shield.
Assume length to be 18 ft. = 5.48 m.

\[D_1 = 8.329 \text{ in.}\]
\[D_2 = 6.25 \text{ in.}\]
\[D_2/D_1 = 6.25/8.329 = 0.750\]

\[C = 79.8 \frac{\text{in.}^2}{\text{s}} \text{ free molecular, } T = 300K, \quad M = 4\]

*This neglects pumping inside of radiation shield.*
How much improvement in the conductance for the obround part if we increase 6.375 in to 6.875 in?

Model as rectangles as on page 2.

Rect. #1 same:

\[ C_{\text{Rect. #1}} = 3.97 \, \text{l/s} \]

Rect. #2:

\[ a = 9.375 + 0.25 \text{in.} = 9.625 \text{in.} \]
\[ b = 2.25 \text{in.} \]

\[ C_{\text{Rect. #2}} = 13.83 \, \text{l/s} \]

\[ C_{\text{Total}} = 2(3.97) + 2(13.83) = 35.6 \, \text{l/s} \]

Quite an improvement.

What if we move the LN2 rad shield by 0.5" to side A?

Rect. #1 same:

\[ C_{\text{Rect. #1}} = 3.97 \, \text{l/s} \] \((\times 2)\)

Rect. #2:

\[ 9.375 \times 2 \Rightarrow C_{\text{Rect. #2}} = 8.78 \]

Rect. #3:

\[ a = 9.375 + 0.5 \text{in.} = 10.875 \text{in.} \]
\[ b = 2.25 \text{in.} \]

\[ C_{\text{Rect. #3}} = 15.0 \, \text{l/s} \]

\[ C_{\text{Total}} = 2(3.97) + 8.78 + 15 = 31.7 \, \text{l/s} \]

It is better to keep LN2 shield centered in vacuum jacket.
Determine what size pumping line is required.

- Look at:
  A) Rectangular Duct
  B) Annular
  C) Circular

Coil operating vacuum must be $10^{-7}$ Torr or less.
- $10^{-6}$ Torr causes significant heat loads & problems
- $4 \times 10^{-6}$ Torr causes quench (gauge reading) $2.2 \times 10^{-5}$ Torr (environment)
- $2 \times 10^{-5}$ Torr during quench (assume gauge reading)

Reference: SSC SDC Design Note A.117 entitled "High Vacuum Pumping of a Helium or Nitrogen Leak in the SDC Solenoid Vacuum Vessel" by A.M. Stefanik, 10-15-90

Method:

1) Find flow regime for different sizes & shapes
2) Calculate conductances for different sizes & shapes
3) Choose shape & configuration of pumping system from chimney to pump. Calculate conductance
4) Calculate throughput for a given size pump and the different size & shapes.
5) Reach conclusion on first iteration.

Sizes & Shapes:

A) Rectangular
   - i) $2.5'' \times 9.5'' = 6.35 \text{ cm} \times 24.13 \text{ cm}$
   - ii) $2.5'' \times 5'' = 6.35 \times 12.7 \text{ cm}$

B) Annular
   - $a = 2.75'', b = 2''$
   - $a = 2.75'' b = 2.5''$

C) Circular
   - i) $2.75''$ I.D.
   - ii) $1''$ I.D.
Flow regime; characterize by Knudsen \( K_n = \frac{\lambda}{D} \)

- Low (rough vacuum): \( K_n < 10^{-2} \)
- Medium vacuum & intermediate flow: \( 10^{-2} < K_n < 0.5 \)
- High/ultra high vacuum & molecular flow: \( K_n > 0.5 \)

\[
K_n = \frac{\lambda}{D}, \quad \lambda = \frac{1}{2\pi} d_0^2 n
\]

- \( d_0 \) is the molecular diameter (m)
- \( n \) is gas density (molecules/m³)

For He: \( d_0 = 0.218 \text{nm} = 0.218 \times 10^{-9} \text{m} \)
For N₂: \( d_0 = 0.375 \text{nm} = 0.375 \times 10^{-9} \text{m} \)

Ideal gas law: \( P = nRT \)

\[
P = \frac{1}{KT}
\]

For \( P = 2.2 \times 10^{-5} \text{torr} = 2.2 \times 10^{-5} \times \frac{1}{760} \text{Pa} = 2.93 \times 10^{-3} \text{Pa} \)
\( T = 80 \text{K} \)

\[
\frac{2.93 \times 10^{-3} \text{Pa}}{(1.3804 \times 10^{-23} \frac{1}{\text{K}})(80 \text{K})} = 2.653 \times 10^{18} \text{m}^3
\]

\[
\lambda_{\text{He}} = \frac{1}{\sqrt{2} (0.218 \times 10^{-9})^2 (2.653 \times 10^{18})} = 5.6 \text{ m}
\]

\[
\lambda_{\text{N}_2} = \frac{1}{\sqrt{2} (0.375 \times 10^{-9})^2 (2.653 \times 10^{18})} = 1.895 \text{ m}
\]

In calculating \( K_n \) use the hydraulic diameter = \frac{4 \times \text{area}}{\text{perimeter}}

1) Rectangular

\[
2.5'' \times 4.5'' \quad K_n = 56.3 \text{ for He} \quad 19 \text{ for N}_2
\]

See Table 1 for these 2 other shape/size results.
IN ALL CASES $\text{Kn} > 0.5$: WE ARE IN THE HIGH/ULTRA HIGH VACUUM + MOLECULAR FLOW REGIME.

(Note: At $T=300\text{K}$, $\text{Kn} \uparrow$, $\text{Kn} \uparrow \approx 300\text{K} \text{Kn}$ even higher?)

*Conductances*

**Rectangular Tube:**

$$C = \left( \frac{32g_{0}R_{u}T}{\pi NM} \right)^{1/2} \frac{a^2 b^2 K}{(a+b) L + 8/3 a b}$$

$a/b \leq 1$ for $A_{i}$; $a/b = 2.5 \rightarrow 3.2$ for $A_{ii}$

$A_{i}$: $a/b = 2.5$  $K \approx 1.25$

$A_{ii}$: $a/b = 0.50$  $K \approx 1.15$

(Ref: Barleon Table 8.1 2nd edition pg. 434-435) 1.3

$c_{0} = 1$

$R_{u} = 8.314 \times 10^{-2} \text{ m}^3 \cdot \text{bar} / \text{kmol} \cdot \text{K}$

$T = 300\text{K}$

$L = 1.84 \text{m}$

$$C_{A_{i}} = \left( \frac{32 (1)(8.314 \times 10^{-2} \text{ m}^3 \cdot \text{bar} / \text{kmol} \cdot \text{K})(300\text{K})^{1/2} (4.03 \times 10^{-3} \text{ m}^2) (5.82 \times 10^{-2} \text{ m}^2)}{9 \pi (4.03 \times 10^{-3} \text{ m}^2)(3.048 \times 10^{-1})(1.84 \text{m}) + 8/3 (1.84 \text{m})} \right)^{1/2} (4.88 \times 10^{-4} \text{ m}^2)$$

$$C_{A_{ii}} = \left( \frac{7.0571 \text{ m}^3 \cdot \text{bar}}{\text{kg}} \right)^{1/2} (4.88 \times 10^{-4} \text{ m}^2)$$
**Fermilab Engineering Note**

**Subject:** DR Solenoid Chimney  
**Vacuum**

\[ C_{A_1} = \left( \frac{7.0571 \text{ m}^2 \cdot \text{bar}}{\text{kg}} \times \frac{10^5 \text{ N/m}^2}{1 \text{ bar}} \times \frac{1 \text{ km}}{1 \text{ m}} \right) \frac{1}{2} \left( 4.88 \times 10^4 \text{ m}^2 \right) = 0.4095 \text{ m}^2 \]  
\[ \times 1000 \frac{L}{\text{m}^3} = 409.5 \text{ L/s} = 410.75 \text{ L/s} \]

I set this up in TK Solver (Mac Application) to do the calculations for this and other rectangular size/condition. See Table 2 for results.

**Annular Tube:** (Ref. Same as Barron Table 8.1)

\[ C = \left( \frac{\pi g R_u T}{18 \text{ m}} \right) \frac{1}{2} \frac{(D_1 - D_2)^2 (D_1 + D_2) K}{L + (4/3)(D_1 - D_2)} \]

Where \( K \) is read off of Table 2.

\( D_1 \) is big dia.  
\( D_2 \) is small dia.

From comparison to an "old" version of this eqn in Barron 1st Edition, I conclude that there is a misprint in the formula. The "correct" formula should be:

\[ C = \left( \frac{\pi g R_u T}{18 \text{ m}} \right) \frac{1}{2} \frac{(D_1 - D_2)^2 (D_1 + D_2) K}{L + (4/3)(D_1 - D_2)} \]

old formula was:

\[ C = \left( \frac{\pi g R_u T}{18 \text{ m}} \right) \frac{1}{2} \frac{(D_1 - D_2)^2 (D_1 + D_2) K}{L} \]

For 2.75" \( \phi \) x 2" \( \phi \)

\[ C = \left( \frac{\pi (1)(8314 \frac{1}{(273 + 273)})(300 \times 10^3)}{18 \left( 4 \times 10^3 \frac{\text{kg}}{\text{m}^3} \right)} \right) \frac{1}{2} \left( 0.1905 \text{ m}^2 \right) \left( 0.01265 \text{ m} \right)^2 1.276 = 0.0988 \text{ m}^3 \]

\[ D_2^2 / D_1 = \frac{2^2}{2.75} = 0.727 \quad \Rightarrow \quad K = 1.276 \]

\[ C = 9.9 L/s \]

I set this up in TK Solver, see Table 2 for results of other sizes/temps, gas.

For 2.75" \( \phi \) x 2.5" \( \phi \), \( D_2^2 / D_1 = 0.909 \), \( K = 1.536 \)

**Circular Tube:**

\[ C = \left( \frac{\pi g R_u T}{18 \text{ m}} \right) \frac{1}{2} \frac{D_1^3}{L} \]

**Barraan 250 - Table 8.1**

**CDF**

\[ D_2^2 / D_1 = 0.798 \quad K = 1.3547 \quad L = 3.48 \text{ m} \]

**SDC**

Reference A. Stefanik Calc., SDC Design Note 117.

Biggest contribution in C, annular wall: 34", 12.4" \( \phi \) @ 8.1".
### Table 2 - Conductance of Different Shapes & Sizes

(L = 1.84 m, Free Molecular Flow, Temp, & Gas Noted)

<table>
<thead>
<tr>
<th>SIZE</th>
<th>$C_{300K}$ (He)</th>
<th>$C_{300K}$ ($N_2$)</th>
<th>$C_{80K}$ (He)</th>
<th>$C_{80K}$ ($N_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangle A:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5&quot; x 9.5&quot;</td>
<td>410 L/s</td>
<td>155 L/s</td>
<td>212 L/s</td>
<td>80 L/s</td>
</tr>
<tr>
<td>Rectangle A II:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5&quot; x 5&quot;</td>
<td>169</td>
<td>64</td>
<td>87</td>
<td>33</td>
</tr>
<tr>
<td>Annular B:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.75&quot; x 2&quot;</td>
<td>9.9</td>
<td>3.7</td>
<td>5.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Annular B II:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.75&quot; x 2.5&quot;</td>
<td>1.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Circular 2.75&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.75&quot;</td>
<td>61</td>
<td>23</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>Circular 1&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot;</td>
<td>2.9</td>
<td>1.1</td>
<td>1.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Annular (COP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.203 m x 0.162 m</td>
<td>78</td>
<td>29</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>Circular 2.75&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.75&quot;</td>
<td>141</td>
<td>53</td>
<td>73</td>
<td>27</td>
</tr>
<tr>
<td>SDC Complete Line 6&quot; Ø to Pump</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>47</td>
<td>65</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

If DØ is to achieve pumping speeds comparable to COP or those available for SDC, it looks clear from the above table that DØ will require a separate pumping line or employ some other "trick" like placing a pump closer to the solenoid.
Look at Throughput/Pumping Speed

Once the pumping path is out of the crack, assume we can run a 4" Sch. 5 pipe to the pump.

Imagine pump is located near Control Dewar.

Run would contain: about 35' of 4" Sch. 5 pipe
5 elbows (short radius)
2 gate valves.

Do all calls for T=300K, u=4 (He), P=2.2x10^-5 torr, free molecular

Pipe: 4" Sch. 5, i.d. = 4.5" - 2(0.083") = 4.33 in.

South

East

8 ft. pipe, short tube L = 2.438 m

\[ C = \left( \frac{\pi \sqrt{Rr}}{18u} \right)^2 \left( \frac{L + \frac{4}{3}}{D^2} \right)^2 = 1.698 = 170 \ L/s \]

2 ft. pipe, short tube L = 0.6096 m

\[ C = 580 \ L/s \]

20 ft. pipe, long tube L = 6.096 m

\[ C = 72 \ L/s \]

5 ft. pipe, short tube L = 1.524 m

\[ C = 263 \ L/s \]

Elbow

Because of space limitations assume short radius.

\[ d = 4.33" \quad \gamma_1 = 4.33 \approx 1 \Rightarrow \gamma = 0.05 \]

\[ \gamma = 4" \]

\[ C = \left( \frac{2 \gamma_1 R_1 \gamma}{\pi M u^2} \right)^{1/2} D^3 \]

\[ C = \left( \frac{2 \gamma_1 R_1 \gamma}{\pi (4)} \right)^{1/2} \left( \frac{\pi 0.998}{\pi 1.016} \right)^3 = 2.75 \ m^3/s \times \frac{1000 L}{1 m^3} = 2750 \ L/s \]
**GATE VALVE:** High vacuum gate valve, 4" Free Molarion Flow

\[
\frac{1}{C} = \frac{1}{C_i} = \frac{5}{2750} + \frac{1}{170} + \frac{1}{580} + \frac{1}{72} + \frac{1}{263}
\]

\[
C = 36.9 \text{ in} \times 3.7 \text{ in} (4" \\
\text{APE SIZE})
\]

For an example consider using a Turbomolecular Turbo Pump w/ 4" APE Flange:

\[
S = 380 \text{ in} \times \text{ in}
\]

\[
\Rightarrow \text{EFFECTIVE PUMPING SPEED}:
\]

\[
\frac{1}{S_{\text{eff}}} = \frac{1}{S_{\text{nom}}} + \frac{1}{C_{\text{EXTERNAL LINE TO PUMP}}} + \frac{1}{C_{\text{CHIMNEY}}}
\]

Using the above equation and data in Table 2, we can construct Table 3.

Running thru the first size # shape, Al

\[
\frac{1}{S_{\text{eff}}} = \frac{1}{380} + \frac{1}{37} + \frac{1}{410} \Rightarrow S_{\text{eff}} = 31.1 \text{ in} = 31 \text{ in}
\]

From the data in Table 3, it is obvious that the external line conductance (37 in) needs to be improved.
### Table 3: Pumping Speed Comparison

<table>
<thead>
<tr>
<th>Size/Shape</th>
<th>Chimney Conductance</th>
<th>External Line Conductance</th>
<th>Nominal Pump Speed</th>
<th>Effective Pump Speed @ Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(l/s)</td>
<td>(4&quot; pipe - size) (l/s)</td>
<td>(l/s)</td>
<td>(l/s)</td>
</tr>
<tr>
<td>Rect. 2.5&quot; x 9.5&quot;</td>
<td>410</td>
<td>37</td>
<td>380</td>
<td>31</td>
</tr>
<tr>
<td>Rect. 2.5&quot; x 5&quot;</td>
<td>169</td>
<td>37</td>
<td>380</td>
<td>28</td>
</tr>
<tr>
<td>Annular, 2.75&quot;ø x 2&quot;ø</td>
<td>10</td>
<td>37</td>
<td>380</td>
<td>8</td>
</tr>
<tr>
<td>Annular, 2.75&quot;ø x 2.5&quot;ø</td>
<td>2</td>
<td>37</td>
<td>380</td>
<td>1</td>
</tr>
<tr>
<td>Circular, 1&quot; ø</td>
<td>3</td>
<td>37</td>
<td>380</td>
<td>3</td>
</tr>
<tr>
<td>Circular, 2.75&quot;ø</td>
<td>61</td>
<td>37</td>
<td>380</td>
<td>22</td>
</tr>
<tr>
<td>Circular, 3&quot; O.D. x .065&quot; wall</td>
<td>69</td>
<td>37</td>
<td>380</td>
<td>23</td>
</tr>
<tr>
<td>CDF, both pumps on</td>
<td></td>
<td></td>
<td></td>
<td>59</td>
</tr>
<tr>
<td>CDF, control dewar pump only</td>
<td></td>
<td></td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>SDC 4&quot;ø to pump</td>
<td>total 125</td>
<td></td>
<td>390</td>
<td>95</td>
</tr>
</tbody>
</table>

Required pump speed to keep the coil at 2.2 \times 10^{-7} Torr with a warm 10^{-8} atm-cc/sec leak leaking cold LHe is \(4\ l/s\).

Temperature used in calculations is 300K.
Assumed pumping helium gas.
Conductances are for free molecular flow regime.
- Estimate pumping speed required.

\[ P_{\text{th}} = \frac{Q_i}{S_3} \]

Volume of vacuum chamber:

\[ V = \pi (r^2 - r_i^2) L = \pi (0.71 m - 0.575 m) (2.7 m) = 1.47 m^3 \]

Say about 1/2 of that volume is conductor, bobbin etc.

\[ V_{\text{empty}} = 0.7 m^3 \times \frac{1000 L}{1 m^3} = 700 \text{Litres} \]

\[ P_{\text{th}} = 2.2 \times 10^{-7} \text{Torr} \]

Guess \( Q \), solve for \( S_3 \), effective pump speed required.

\( Q \): inleak rate due to virtual leaks, real leaks, and outgassing.

Assume that during fabrication & leak checking, a leak in the helium circuit of size \( 1 \times 10^{-10} \text{ atm-cc/sec} \) goes unnoticed. How much leak is that when liquid He flows through the line & vacuum space is \( \varnothing \) vacuum?

Minimum detectable leak \( \approx 10^{-9} \text{ Pa-L/s} \)

\[ Q_{\text{leak}} = 10^{-9} \frac{\text{Pa-L}}{s} \times \frac{760 \text{ Torr}}{1.013 \times 10^5 \text{ Pa}} = 7.5 \times 10^{-12} \text{ Torr-L/s} \]

\( Q \) assumed is \( 1 \times 10^{-10} \text{ atm-cc/sec} \times \frac{760 \text{ Torr}}{1 \text{ atm}} \times \frac{1 \text{ L}}{1000 \text{ cc}} \times 7.6 \times 10^{-11} \text{ Torr-L/sec} \)

\[ Q_{\text{assumed}} = 7.6 \times 10^{-11} \text{ Torr-L/sec} \]

Use assumed leak.

Model the 'leak' as choked flow. That is gas flows at its sonic velocity thru the hole/path.

\[ V_s|_{\text{He}} = 1100 m/s \quad \rho_{\text{He}} = 1.625 kg/m^3 \]

\[ m = \rho V A \]

\[ m|_{\text{assumed}} = 1 \times 10^{-10} \frac{\text{atm-cc}}{\text{sec}} \times \frac{\rho}{V} = 1 \times 10^{-10} \frac{\text{cm}^3}{\text{sec}} \times 1.625 \frac{\text{kg}}{\text{m}^3} \times \frac{1 L}{1000 \text{cm}^3} \times \frac{1 L}{1000 L} \]

\[ m|_{\text{assumed}} = 1.625 \times 10^{-14} \text{ kg/s} \]

\[ \rho|_{\text{assumed}} = 1.625 \times 10^{-14} \text{ kg/s} \]
SOLVING FOR A THEORETICAL \( A \),

\[
A = \frac{m}{\rho v_s} = \frac{1.625 \times 10^{-14} \text{ kg/s}}{0.1625 \times \frac{\text{kg}}{M^3} (1100 \text{ kg/m}^3)} \times \frac{1}{1000 \text{ g}} = 9.09 \times 10^{-20} \text{ m}^2
\]

DETERMINE LIQUID FLOW RATE AT 'COLD' RUNNING CONDITION.

\[
\dot{m} = \dot{p} \dot{v} A = (1.249 \frac{\text{ kg}}{\text{ m}^3})(177 \text{ m}^3)(9.09 \times 10^{-20} \text{ m}^2) \times \left(\frac{1000 \text{ g}}{1 \text{ kg}}\right)
\]

\[
\dot{m} = 2.0 \times 10^{-12} \text{ g/s}
\]

THIS COLD MASS FLOW RATE WILL BE WARMED UP TO 300K.

CONVERTING THE COLD MASS FLOW RATE TO WATTS PUMP LOAD UNITS

\[
\dot{Q}_{\text{leak}} = 2.0 \times 10^{-12} \text{ g/s} \times \frac{1 \times 10^{-10} \text{ atm-cL}}{\text{sec}} = 1.24 \times 10^{-20} \frac{\text{ atm-cL}}{\text{sec}}
\]

\[
= 1.24 \times 10^{-8} \text{ atm-cL} \times \frac{760 \text{ torr}}{1 \text{ atm}} \times \frac{1 \text{ L}}{1000 \text{ cc}} = 9.4 \times 10^{-9} \text{ torr-L/sec}
\]

OUTGASSING: EVENTUALLY OUTGASSING ISN'T A FACTOR SINCE IT DECREASES EXPONENTIALY ON TIME

\[
\dot{q} = q e^{-\alpha \cdot \text{time}}
\]

SURFACE AREA OF SHELL = \( 2 \pi (r_1 + r_2) \text{ L} + \pi (r_2^2 - r_1^2) \)

\[
A_{\text{shell}} = 2 \pi (0.71m + 0.575m)(2.7m) + \pi (0.71m^2 - 0.575m^2) = 22.3 \text{ m}^2
\]

\[
A_{\text{bobbin}} = 2 \pi (-0.66m + 0.61m)(2.7m) = 2.15 \text{ m}^2 \quad (A.L. 5083)
\]

\[
A_{\text{chimney}} = \pi DL = \pi (4.33 \text{ in.})(15 \text{ in}) \div \frac{254 \text{ m}}{1 \text{ in.}} = 5.2 \text{ m}^2
\]
ENGINEERING NOTE

SUBJECT: DO SOLENOID CHIMNEY

VACUUM

Amplak = 8 layers \times 22 m^2/layer = 176 m^2 = 180 m^2

\[ Q_{out} = \sum_i A_i = \left( 1 \times 10^{-6} \frac{\text{Torr-L}}{\text{m}^2} \right) (5.2 m^2) + \left( 2 \times 10^{-6} \frac{\text{Torr-L}}{\text{m}^2} \right) (4.4 m^2) + \left( 7 \times 10^{-5} \frac{\text{Torr-L}}{\text{m}^2} \right) (180 m^2) \]

= 0.0127 \frac{\text{Torr-L}}{\text{sec}} < 6 \text{ orders of magnitude larger than } Q_{\text{leak!}}

Comparison Note: CDF leak rate w/ liquid helium was
\[ 1.5 \times 10^{-7} \frac{\text{Atm-cm}}{\text{sec}} = 1.1 \times 10^{-7} \frac{\text{Torr-L}}{\text{sec}} \]

Reference Note 117

After conference w/ Kurt Krampete we conclude outgassing load will be cryo-pumped. I will therefore only worry about possible leaks.

For calculation of required pumping speed assume technician misses a. \( 1 \times 10^{-8} \frac{\text{Atm-cm}}{\text{sec}} \) leak (see pg 940 for \( 1 \times 10^{-10} \frac{\text{Atm-cm}}{\text{sec}} \))

\[ Q_{\text{leak}} = 1.24 \times 10^{-8} \frac{\text{Atm-cm}}{\text{sec}} = 9.4 \times 10^{-7} \frac{\text{Torr-L}}{\text{sec}} \]

\[ S_s = \frac{Q_{atm}}{Q_{\text{leak}}} = \frac{9.4 \times 10^{-7} \frac{\text{Torr-L}}{\text{sec}}}{2.2 \times 10^{-9} \frac{\text{Torr-L}}{\text{sec}}} = 4.3 \frac{\text{L/s}}{\text{atm}} \]

Comparison Note: CDF effective pumping speed (on coil)
Free molecular flow regime is:

\[ S_s_{\text{CDF}} = 59 \frac{\text{L/s}}{} \text{ for both pumps pumping} \]
\[ = 42 \frac{\text{L/s}}{} \text{ for control dewar pump on only} \]

Reference Bruce Squires phone conversation 10/12/92

We should be shooting for \( 4.3 \frac{\text{L/s}}{} < S_s < 50 \frac{\text{L/s}}{} \)
For the 'crack' part of the chimney we could use 3" O.D. x 0.065" wall tubing.

I.D. = 2.87"

Conductance calculates to be 69.45 ≈ 69 4/5 \text{ L/s} \text{ for } 300 \text{ K}

From design chart of long vacuum pipes min wall thickness for F.S. = 2 for 3" dia. 15.03" = this applies only to true circular shapes since our pipe will be shorter however it fixed at the ends the out of roundness/curved shape effect will probably not increase the req'd thickness.

The external pumping line will have to be improved from 4" pipe.

Note: The following equations hold for the vacuum system.

\[ S_p = \frac{Q}{P}; \quad C_0 = \frac{Q}{P} \left( \frac{P}{P_i} - 1 \right) \]

\[ S_s = \frac{Q}{P} \quad \frac{1}{S_s} = \frac{1}{S_p} + \frac{1}{C_0} \]

For \( S_p = 380 \text{ L/s} \), \( C_1 = 24 \text{ L/s} = \left( \frac{4}{5} \right) \text{ L/s} \)

\[ P = 2.2 \times 10^{-7} \text{ Torr} \]

We solve the equations to show

\[ P_i = 1.3 \times 10^{-8} \text{ Torr} \quad S_s = 22.615 \approx 22 \text{ L/s} \] as shown in Table 3

\[ Q = 3 \times 10^{-6} \text{ Torr} \cdot \text{L/s} \]

For TMP. 361, \( P_{\text{atm}} = <10^{-10} \text{ mbar} = <7.5 \times 10^{-11} \text{ Torr} \)

In general for conductance range we're in pressure at the solenoid will be one order of magnitude higher than at the pump.