APPLIED ION SYSTEMS

High Vacuum Engineering Calculations

Small Scale Multipurpose High Vacuum System V5 Design – Full Pumping System Assembly

Ultimate Pressure and System Gas Load Due to Outgassing for Pumpdown

1.) Maximum Theoretical Gas Loads for Ultimate Operating Pressures at Various Flows

a.) Ultimate Pressure vs. Working Pressure – Ideal Minimum Ratio

$$P_u = \frac{P_w}{10}$$

$\boldsymbol{P_u}$ (*Ultimate Pressure, Torr*)	$\boldsymbol{P_w}$ (*Working Pressure, Torr*)
$\mathbf{1x10^{-8}}$	$\mathbf{1x10^{-7}}$
$\mathbf{1x10^{-7}}$	$\mathbf{1x10^{-6}}$
$\mathbf{1x10^{-6}}$	$\mathbf{1x10^{-5}}$
$\mathbf{1x10^{-5}}$	$\mathbf{1x10^{-4}}$
$\mathbf{1x10^{-4}}$	$\mathbf{1x10^{-3}}$
$\mathbf{1x10^{-3}}$	$\mathbf{1x10^{-2}}$

b.) Pressure vs. Maximum Allowable Gas Load – Molecular Flow (at the 5-Way Cross Inlet)

$$S_e = \frac{q}{P_u} \rightarrow q = S_e \times P_u$$

$$S_e = 18.620 \ L/s \, for \ Water \ Vapor \ @ \ 20C$$

$\boldsymbol{P}$ (*Pressure, Torr*)	$\boldsymbol{q}$ (*Max Allowable Gas Load, Torr · L/s*)
$\mathbf{1x10^{-8}}$	$\mathbf{1.862\ x\ 10^{-7}}$
$\mathbf{1x10^{-7}}$	$\mathbf{1.862\ x\ 10^{-6}}$
$\mathbf{1x10^{-6}}$	$\mathbf{1.862\ x\ 10^{-5}}$
$\mathbf{1x10^{-5}}$	$\mathbf{1.862\ x\ 10^{-4}}$
$\mathbf{1x10^{-4}}$	$\mathbf{1.862\ x\ 10^{-3}}$

a.) Pressure vs. Maximum Allowable Gas Load –Transitional Flow (at the 5-Way Cross Inlet)

$$S_e = \frac{q}{P_u} \rightarrow q = S_e \times P_u$$

$$S_e = 21.265 \ L/s \, for \ Water \ Vapor \ @ \ 20C$$

$\boldsymbol{P}$ (*Pressure, Torr*)	$\boldsymbol{q}$ (*Max Allowable Gas Load, Torr · L/s*)
$\mathbf{1x10^{-3}}$	$\mathbf{2.127\ x\ 10^{-2}}$
$\mathbf{1x10^{-2}}$	$\mathbf{2.127\ x\ 10^{-1}}$

2.) Total Gas Load

$$Q_{total} = Q_{volume} + Q_{leak} + Q_{outgas} + Q_{diffusion} + Q_{permeation} + Q_{backstreaming} + Q_{process}$$

→ $assuming\ pumpdown\ (Q_{volume} = 0\ for\ bulk\ material), Q_{leak} = 0, Q_{diffusion} = 0, Q_{backstreaming} = 0, Q_{process} = 0, and\ long\ term\ steady\ state\ pumping,$

$$Q_{total} = Q_{outgas} + Q_{permeation}$$

$$Q_{outgas} = Total\ Sum\ of\ Outgassing\ Load \times Area\ per\ n\ Materials\ in\ System$$

$$Q_{outgas} = \sum_{1}^{n} q_{outgas} \times A$$

a.) Gas Load of Diffusion Pump O-Ring

$A_{o\_ring} = 87.553\ cm^2\ (viton)$
$L_{o\_ring} = 43.888\ cm\ (viton)$

i. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_viton} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_o\_ring} = 7.004 \times 10^{-5}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.787 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{diff\_o\_ring\_total} = 7.283 \times 10^{-5} Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr

$QR_{outgas\_rate\_viton} = 2.000 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_o\_ring} = 1.751 \times 10^{-6}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.787 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{diff\_o\_ring\_total} = 4.538 \times 10^{-6}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr

$QR_{outgas\_rate\_viton} = 5.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_o\_ring} = 4.380 \times 10^{-8}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.787 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{diff\_o\_ring\_total} = 2.831 \times 10^{-6}\ Torr \cdot L/s}$

b.) Gas Load of Water Cooled Baffle Adapter:

$A_{baffle\_adapter} = 195.996\ cm^2\ (aluminum)$
$A_{o\_ring} = 71.895\ cm^2\ (viton)$
$L_{o\_ring} = 64.819\ cm\ (viton)$

i. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_aluminum} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$

$Q_{outgas\_baffle\_adapter} = 1.568 \times 10^{-4}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 5.752 \times 10^{-5}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.116 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_adapter\_total} = 2.144 \times 10^{-4}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr
$QR_{outgas\_rate\_aluminum} = 1.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_baffle\_adapter} = 1.960 \times 10^{-8}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 2.000 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 1.438 \times 10^{-6}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.116 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_adapter\_total} = 5.574 \times 10^{-6}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr
$QR_{outgas\_rate\_aluminum} = 5.000 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_baffle\_adapter} = 9.800 \times 10^{-11}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 5.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 3.590 \times 10^{-8}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.116 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_adapter\_total} = 4.152 \times 10^{-6}\ Torr \cdot L/s}$

c.) Gas Load of Water Cooled Baffle
$A_{baffle} = 2374.241\ cm^2\ (stainless\ steel)$
$A_{o\_ring} = 72.528\ cm^2\ (viton)$
$L_{o\_ring} = 65.389\ cm\ (viton)$

i. Unbaked, Pumped 1hr
$QR_{outgas\_rate\_stainless\_steel} = 5.000 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_baffle} = 1.190 \times 10^{-4}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 5.800 \times 10^{-5}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.150 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_total} = 1.810 \times 10^{-4}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr
$QR_{outgas\_rate\_stainless\_steel} = 1.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_baffle} = 2.370 \times 10^{-7}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 2.000 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 1.450 \times 10^{-6}\ Torr \cdot L/s$

$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.150 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_total} = 5.840 \times 10^{-6}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr
$QR_{outgas\_rate\_stainless\_steel} = 3.000 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_baffle} = 7.120 \times 10^{-10}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 3.630 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 8.000 \times 10^{-7}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 4.150 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{baffle\_total} = 4.190 \times 10^{-6}\ Torr \cdot L/s}$

d.) Gas Load of Plate Adapter
$A_{plate\_adapter} = 366.655\ cm^2\ (aluminum)$
$A_{o\_ring} = 34.872\ cm^2\ (viton)$
$L_{o\_ring} = 36.820\ cm\ (viton)$

i. Unbaked, Pumped 1hr
$QR_{outgas\_rate\_aluminum} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_plate\_adapter} = 2.933 \times 10^{-4}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 8.000 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 2.790 \times 10^{-5}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.338 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{plate\_adapter\_total} = 3.236 \times 10^{-4}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr
$QR_{outgas\_rate\_aluminum} = 1.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_plate\_adapter} = 3.667 \times 10^{-8}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 2.000 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 6.974 \times 10^{-7}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.338 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{plate\_adapter\_total} = 3.072 \times 10^{-6}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr
$QR_{outgas\_rate\_aluminum} = 5.000 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_plate\_adapter} = 1.833 \times 10^{-10}\ Torr \cdot L/s$
$QR_{outgas\_rate\_viton} = 5.000 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$
$Q_{outgas\_viton} = 1.744 \times 10^{-8}\ Torr \cdot L/s$
$QR_{permeation\_rate\_viton} = 6.350 \times 10^{-8}\ Torr \cdot L/s \cdot cm$
$Q_{permeation\_o\_ring} = 2.338 \times 10^{-6}\ Torr \cdot L/s$
$\boldsymbol{Q_{plate\_adapter\_total} = 2.356 \times 10^{-6}\ Torr \cdot L/s}$

e.) Gas Load of 6" to 2.75" Conflat Zero Clearance Reducer

$A_{reducer} = 111.85\ cm^2\ (stainless\ steel)$

i. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_stainless\_steel} = 5 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 5.593 \times 10^{-6}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 1 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 1.119 \times 10^{-8}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 3 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 3.356 \times 10^{-11}\ Torr \cdot L/s}$

f.) Gas Load of Cross:

Assuming two blanked ports on the sides for simplicity,

$A_{cross\_main} = 218.032\ cm^2\ (stainless\ steel)$

$A_{cross\_blanks} = 2 \times 10.509\ cm^2\ (stainless\ steel)$

$A_{cross\_total} = 239.050\ cm^2\ (stainless\ steel)$

iv. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_stainless\_steel} = 5 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 1.195 \times 10^{-5}\ Torr \cdot L/s}$

v. Unbaked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 1 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 2.391 \times 10^{-8}\ Torr \cdot L/s}$

vi. Baked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 3 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 7.172 \times 10^{-11}\ Torr \cdot L/s}$

g.) Gas Load of Valve:

$A_{valve} = 58.221\ cm^2\ (stainless\ steel)$

$A_{o\_ring} = 18.281\ cm^2\ (viton)$

$L_{o\_ring} = 13.657\ cm\ (viton)$

i. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_stainless\_steel} = 5 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_viton} = 8 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$

$Q_{outgas\_valve} = 1.754 \times 10^{-5}\ Torr \cdot L/s$

$QR_{permeation\_rate\_viton} = 6.35 \times 10^{-8}\ Torr \cdot L/s \cdot cm$

$Q_{permeation\_o\_ring} = 8.672 \times 10^{-7}\ Torr \cdot L/s$

$\boldsymbol{Q_{valve\ total} = 1.841 \times 10^{-5}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 1 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_viton} = 2 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$

$Q_{outgas\_valve} = 3.714 \times 10^{-7}\ Torr \cdot L/s$

$QR_{permeation\_rate\_viton} = 6.35 \times 10^{-8}\ Torr \cdot L/s \cdot cm$

$Q_{permeation\_o\_ring} = 8.672 \times 10^{-7}\ Torr \cdot L/s$

$\boldsymbol{Q_{baffle\_valve} = 1.239 \times 10^{-6}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 3 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_viton} = 5 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$

$Q_{outgas\_valve} = 9.200 \times 10^{-9}\ Torr \cdot L/s$

$QR_{permeation\_rate\_viton} = 6.35 \times 10^{-8}\ Torr \cdot L/s \cdot cm$

$Q_{permeation\_o\_ring} = 8.672 \times 10^{-7}\ Torr \cdot L/s$

$\boldsymbol{Q_{valve\ total} = 8.764 \times 10^{-7}\ Torr \cdot L/s}$

h.) Gas Load of Chamber:

$A_{chamber\_main} = 314.578\ cm^2\ (stainless\ steel)$

$A_{glass\_viewport} = 10.509\ cm^2\ (glass)$

i. Unbaked, Pumped 1hr

$QR_{outgas\_rate\_stainless\_steel} = 5 \times 10^{-8}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_glass} = 1 \times 10^{-7}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 1.678 \times 10^{-5}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 1 \times 10^{-10}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_glass} = 5 \times 10^{-9}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 2.098 \times 10^{-7}\ Torr \cdot L/s}$

iii. Baked, Pumped >24hr

$QR_{outgas\_rate\_stainless\_steel} = 3 \times 10^{-13}\ Torr \cdot L/s \cdot cm^2$

$QR_{outgas\_rate\_glass} = 2 \times 10^{-9}\ Torr \cdot L/s \cdot cm^2$

$\boldsymbol{Q_{cross\ total} = 2.110 \times 10^{-8}\ Torr \cdot L/s}$

i.) TOTAL GAS LOAD:

i. Unbaked, Pumped 1hr

$$Q_{total} = Q_{diff\_o\_ring\_total} + Q_{baffle\_adapter\_total} + Q_{baffle\_total} + Q_{plate\_adapter\_total} + Q_{reducer} + Q_{cross\_total} + Q_{valve\_total} + Q_{chamber\_total}$$

$$Q_{total} = 7.283 \times 10^{-5} + 2.144 \times 10^{-4} + 1.810 \times 10^{-4} + 3.236 \times 10^{-4} + 5.593 \times 10^{-6} + 1.195 \times 10^{-5} + 1.841 \times 10^{-5} + 1.678 \times 10^{-5}$$

$\boldsymbol{Q_{total} = 3.462 \times 10^{-5}\ Torr \cdot L/s}$

ii. Unbaked, Pumped >24hr

$$Q_{total} = Q_{diff\_o\_ring\_total} + Q_{baffle\_adapter\_total} + Q_{baffle\_total} + Q_{plate\_adapter\_total} + Q_{reducer} + Q_{cross\_total} + Q_{valve\_total} + Q_{chamber\_total}$$

$$Q_{total} = 4.538 \times 10^{-6} + 5.574 \times 10^{-6} + 5.840 \times 10^{-6} + 3.072 \times 10^{-6} + 1.119 \times 10^{-10} + 2.391 \times 10^{-8} + 1.239 \times 10^{-6} + 2.098 \times 10^{-7}$$

$$\boldsymbol{Q_{total} = 1.429 \times 10^{-5}\ Torr \cdot L/s}$$

iii. Baked, Pumped >24hr

$$Q_{total} = Q_{diff\_o\_ring\_total} + Q_{baffle\_adapter\_total} + Q_{baffle\_total} + Q_{plate\_adapter\_total} + Q_{reducer} + Q_{cross\_total} + Q_{valve\_total} + Q_{chamber\_total}$$

$$Q_{total} = 2.831 \times 10^{-6} + 4.152 \times 10^{-6} + 4.190 \times 10^{-6} + 2.356 \times 10^{-6} + 3.356 \times 10^{-11} + 7.172 \times 10^{-11} + 8.764 \times 10^{-7} + 2.110 \times 10^{-8}$$

$$\boldsymbol{Q_{total} = 9.589 \times 10^{-6}\ Torr \cdot L/s}$$

4.) Maximum Achievable Vacuum During Pumpdown (at the 5-Way Cross Inlet)

a.) Unbaked, Pumped 1hr

$$S_e = \frac{q}{P_u}$$

$$P_u = \frac{q}{S_e}$$

$S_e = 18.620\ L/s\ for\ Water\ Vapor\ @\ 20C\ in\ Molecular\ Flow$

$q = 3.462 \times 10^{-5}\ Torr \cdot L/s\ Unbaked, Pumped < 1hr$

$\boldsymbol{P_u = 1.859 \times 10^{-6}\ Torr}$

b.) Unbaked, Pumped >24hr

$$S_e = \frac{q}{P_u}$$

$$P_u = \frac{q}{S_e}$$

$S_e = 18.620\ L/s\ for\ Water\ Vapor\ @\ 20C\ in\ Molecular\ Flow$

$q = 1.429 \times 10^{-5}\ Torr \cdot L/s\ Unbaked, Pumped > 24hr$

$\boldsymbol{P_u = 7.675 \times 10^{-7}\ Torr}$

c.) Baked, Pumped >24hr

$$S_e = \frac{q}{P_u}$$

$$P_u = \frac{q}{S_e}$$

$S_e = 18.620\ L/s\ for\ Water\ Vapor\ @\ 20C\ in\ Molecular\ Flow$

$q = 9.589 \times 10^{-6}\ Torr \cdot L/s\ Baked, Pumped > 24hr$

$\boldsymbol{P_u = 5.150 \times 10^{-7}\ Torr}$

5.) Critical Factor Determination for Feasibility of Pumping System

$\rightarrow Critical\ Pumping\ Speed \geq 0.01\ L/s/cm^2$

$\rightarrow Critical\ Pumping\ Speed = 18.620\ L/s\ /985.411\ cm^2$

$\boldsymbol{\rightarrow Critical\ Pumping\ Speed = 0.019\ L/s/cm^2\ (only\ internal\ area)}$

$\rightarrow Critical\ Pumping\ Speed = 18.620\ L/s\ /1213.951\ cm^2$

$\boldsymbol{\rightarrow Critical\ Pumping\ Speed = 0.015\ L/s/cm^2\ (including\ o-ring\ area)}$

$\rightarrow$ ***Critical Pumping Speed IS VALID***