PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-033
REV.	DEO #	DATE	BY:	CHECK		PAGE 1 OF 26
Ø	ØØ38	1/3/96	D. Moore	D.M.W	TITLE: Heat Load Calculations on Clean (No frost) 80K Pumps from Beam Tube & Vacuum Chamber	
1	ØØ52	1/29/96	D. Moore	D.M.W		
2	C246	8/20/96	D. Moore	[illegible]		
					By: David Moore	DEPT.: 744

PROJECT: LIGO

PROJECT NO: V59049

PURPOSE: To determine heat loads on long and short pumps in their clean condition due to thermal radiation exchange with the pump vacuum chamber and the beam tube.

METHOD: Radiation network equations.

ASSUMPTIONS: 1. One radiation shield in the vacuum annulus surrounding the pump LN_2 reservoir.
2. Low emissivity (.06) thermal sleeves in beam tube.
3. Pumps in clean condition.

INPUTS:

REFERENCES: 1. Heat Transfer, J.P. Holman, 3rd ed., McGraw-Hill.
2. Thermal Radiation Heat Transfer, Siegel & Howell, McGraw-Hill

CALCULATIONS: (SEE ATTACHED)

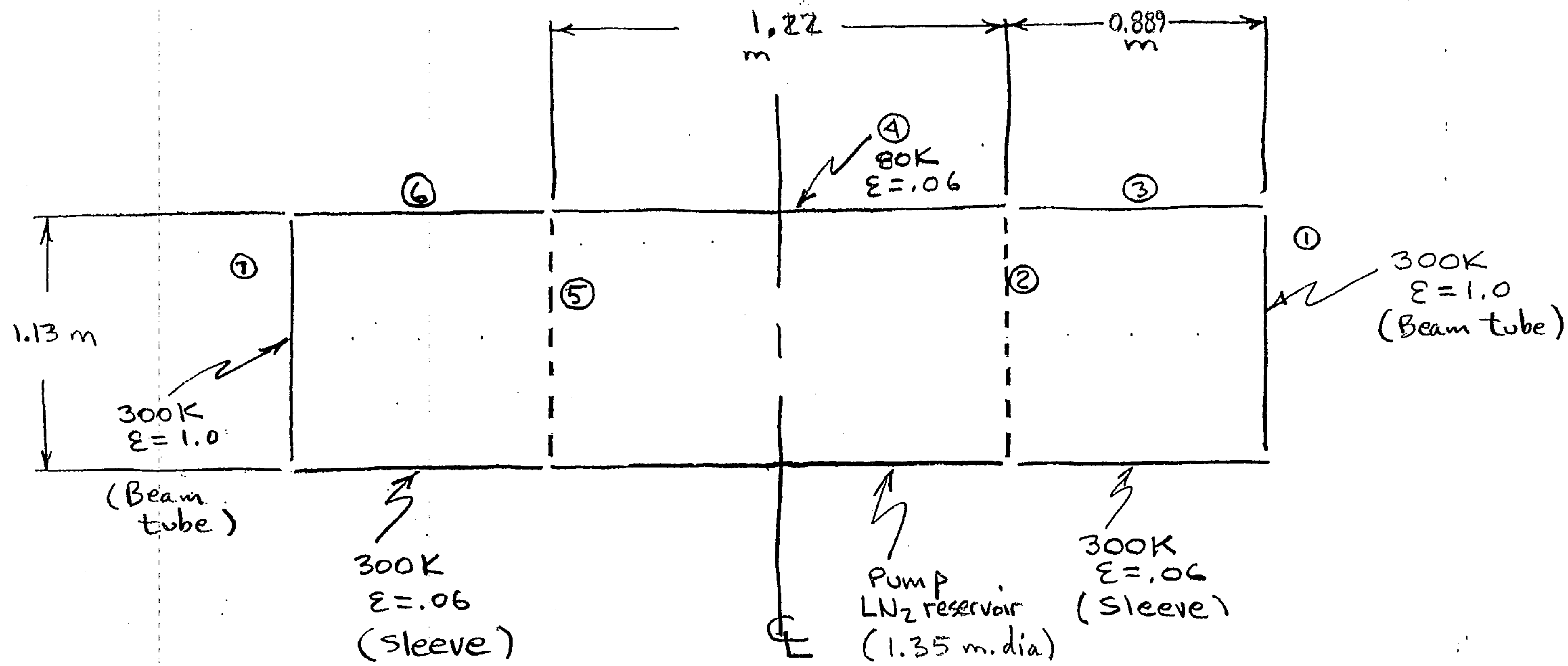
CONCLUSIONS: Radiation shield temp. = 269.5 K

Long Pump (clean):
258 watts (from beam tube)
176 watts (from vac. cham.)
434 watts Total

Short Pump (clean):
117.0 watts
64.0 watts
181.0 total

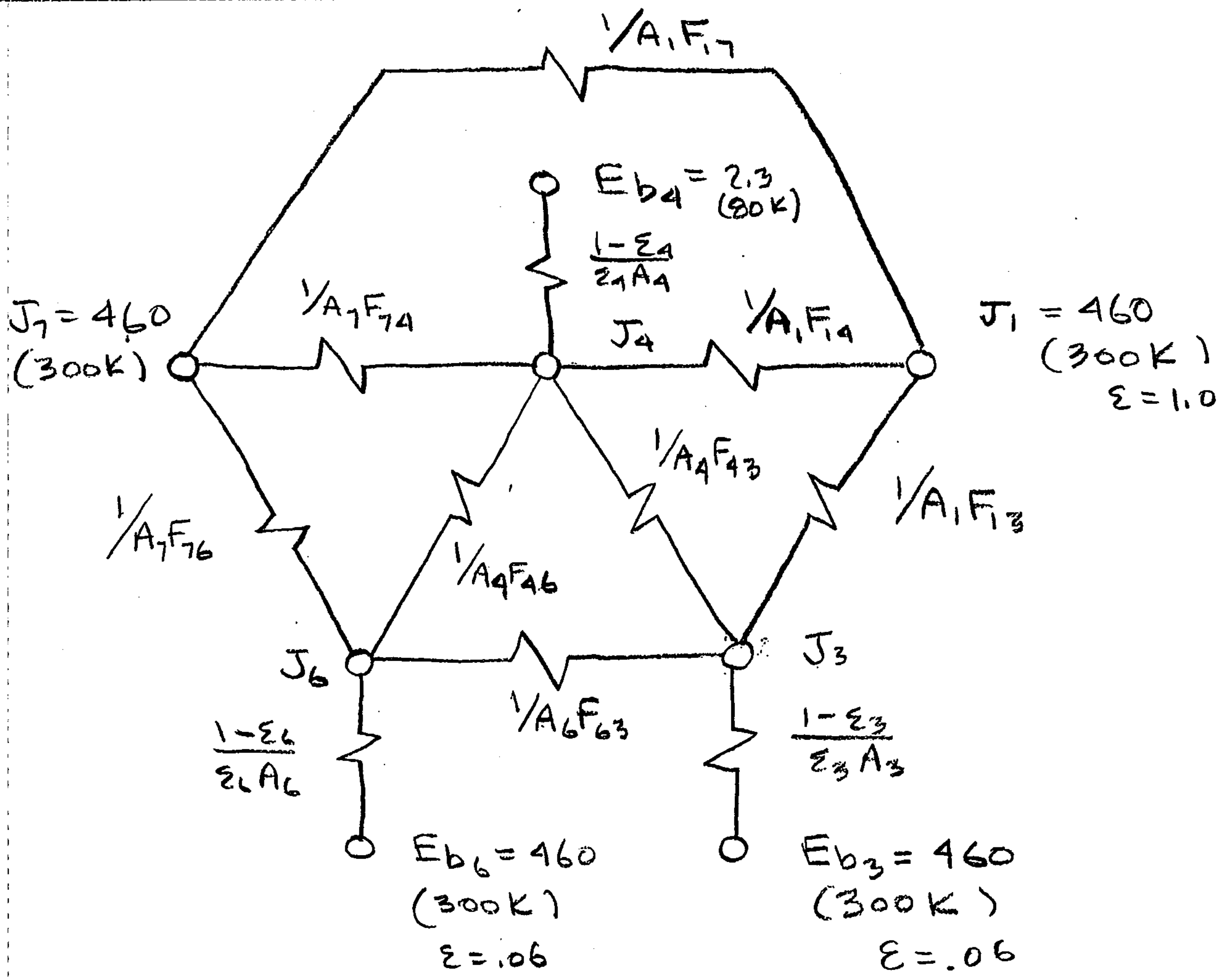
NOTES:

Short Pump
(No Frost)



Surfaces ② & ⑤ are fictitious surfaces used to simplify view factor calculations

V049-1-033
Pg 2 of 23



Clean Pump

$\varepsilon_4 = .06$

V049-1-033

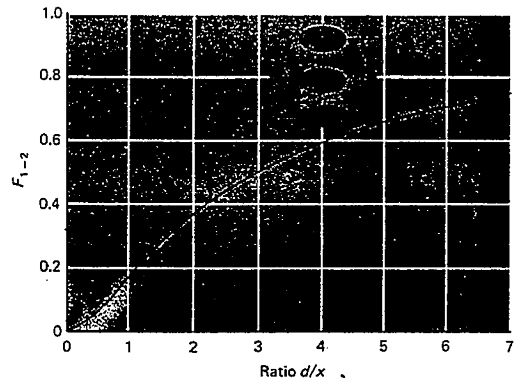
Pg 3 of 23

View Factors

F_{12} : $\frac{d}{x} = \frac{1.13}{0.889} = 1.27$

$\therefore F_{12} = 0.25$ (Heat Transfer, Holman, 3rd ed., pp. 249)

Fig. 8-13 Radiation shape factor for radiation between parallel disks.



$F_{13} = 1 - F_{12}$
$= 0.75$

F_{15} : $\frac{d}{x} = \frac{1.13}{(.889 + 1.22)} \doteq 0.54$

$F_{15} = 0.07$

$\therefore F_{14} = F_{12} - F_{15}$
$= 0.25 - 0.07 = 0.18$

F_{17} : $\frac{d}{x} = \frac{1.13}{2(.889) + 1.22} = 0.38$

$F_{17} = 0.04$

$F_{76} = F_{13} = 0.75$

$F_{41} = \frac{A_1}{A_4} F_{14} = \frac{\pi/4\,(1.13)^2}{\pi(1.13)(1.22)}(.18)$

$F_{41} = .042$

F_{25} : $\frac{d}{x} = \frac{1.12}{1.22} = 0.92$

$F_{25} = 0.15$ $F_{24} = 1 - F_{25}$
$= 0.85$

$$F_{42} = \frac{A_2}{A_4} F_{24}$$

$$= \frac{(\pi/4)(1.13)^2}{\pi(1.13)(1.22)} (.85)$$

$$= 0.197$$

$$F_{43} = F_{42} - F_{41}$$

$$= 0.197 - .042$$

$$= 0.15$$

Surface resistances

$$\frac{1-\varepsilon_4}{\varepsilon_4 A_4} = \frac{1-.06}{.06\pi(1.35)(1.22)}$$

$$= 3.03$$

$$\frac{1-\varepsilon_3}{\varepsilon_3 A_3} = \frac{1-0.06}{.06\pi(1.13)(.889)}$$

$$= 4.96$$

Geometry resistance:

$$\frac{1}{A_1 F_{14}} = 1/\left(\frac{\pi}{4}(1.13)^2(.18)\right) = 5.54$$

$$\frac{1}{A_4 F_{43}} = 1/\left(\pi(1.13\ (1.22)(.15)\right) = 1.54$$

$$\frac{1}{A_1 F_{13}} = 1/\left(\frac{\pi}{4}(1.13)^2(.75\right) = 1.33$$

Sum currents

$$④ \quad \frac{2.3 - J_4}{3.03} + 2\frac{(460 - J_4)}{5.54} + 2\frac{(J_3 - J_4)}{1.54} = 0$$

$$(J_3 = J_6)$$

$$③ \quad \frac{460 - J_3}{1.33} + \frac{460 - J_3}{4.96} + \frac{J_4 - J_3}{1.54} = 0$$

From ④

$$.759 - .330 J_4 + 166.06 - .36 J_4$$
$$+ 1.30 J_3 - 1.30 J_4 = 0$$

$$1.30 J_3 - 1.99 J_4 = -166.82$$

From ③

$$345.86 - .752 J_3 + 92.74 - .202 J_3$$
$$+ .650 (J_4 - J_3) = 0$$

$$-1.604 J_3 + .650 J_4 = -438.60$$

1.3	-1.99	matrix	-166.82	constants
-1.604	0.65		-438.6	

-0.27695	-0.84791	inverse
-0.68344	-0.55391	

J3=	418.0928	solution
J4=	356.9551	

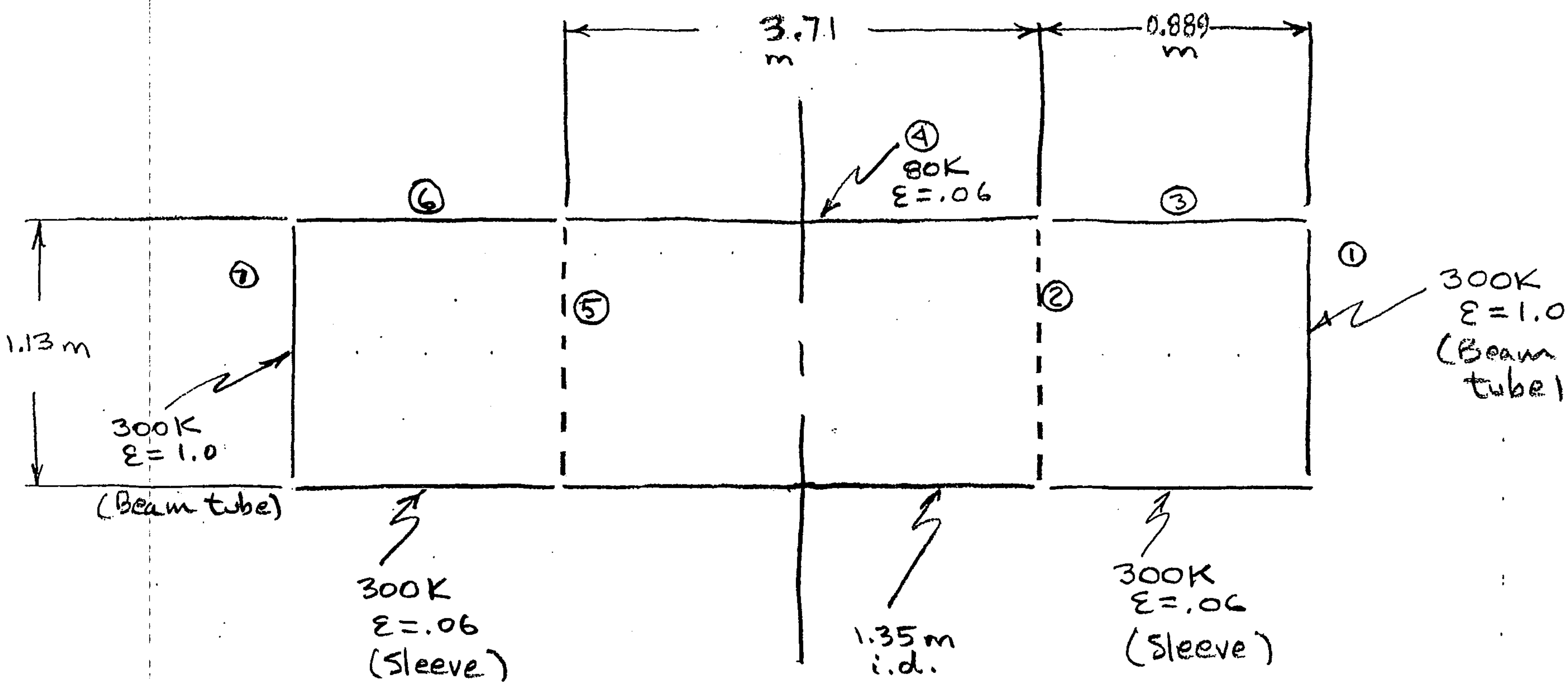
V049-1-033

$$Q_4 = (J_4 - E_{b4}) \Big/ \frac{1-\varepsilon_4}{\varepsilon_4 A_4}$$

$$= (356.96 - 2.3) / 3.03$$

$$= 117 \text{ watts}$$

Long Pump
(No Frost)



Surfaces ② & ⑤ are fictitious surfaces used to simplify view factor calculations.

View Factors:

F_{12}: $\frac{d}{x} = \frac{1.13}{.889} = 1.27$

$\therefore F_{12} = .25$ (Heat Transfer, Holman, 3rd ed., pp 249)

$F_{13} = 1 - F_{12}$
$= .75$

F_{15}: $\frac{d}{x} = \frac{1.13}{(.889+3.71)} = .245$

$F_{15} = 0.03$

$\therefore F_{14} = F_{12} - F_{15}$
$= .12 - .03 = .09$

F_{17}: $\frac{d}{x} = \frac{1.13}{2(.889)+3.71} = .205$ $F_{17} = .025$

$F_{76} = F_{13} = .75$

$F_{41} = \frac{A_1}{A_4} F_{14} = \frac{\pi/4\,(1.13)^2}{\pi\,(1.13)(3.71)}(.09)$

$F_{41} = .007$

F_{25}: $\frac{d}{x} = \frac{1.13}{3.71} = .30$

$F_{25} = .04$ $\therefore F_{24} = 1 - F_{25}$
$= .96$

$$F_{42} = \frac{A_2}{A_4} F_{24}$$

$$= \frac{(\pi/4)(1.13)^2}{\pi(1.13)(3.71)} (.96)$$

$$= .073$$

$$F_{43} = F_{42} - F_{41}$$

$$= .073 - .007$$

$$= .066$$

Surface resistances:

$$\frac{1-\varepsilon_4}{\varepsilon_4 A_4} = \frac{1-.06}{.06(\pi)(1.35)(3.71)}$$

$$= 1.00$$

$$\frac{1-\varepsilon_3}{\varepsilon_3 A_3} = \frac{1-.06}{.06(\pi)(1.13)(1.5)}$$

$$= 2.94$$

Geometry resistance:

$$\frac{1}{A_1 F_{14}} = \frac{1}{\frac{\pi}{4}(1.13)^2(.09)} = 11.08$$

$$\frac{1}{A_4 F_{43}} = \frac{1}{\pi(1.35)(3.71)(.066)} = 0.97$$

$$\frac{1}{A_1 F_{13}} = \frac{1}{\frac{\pi}{4}(1.13)^2(.75)} = 1.33$$

V049-1-033

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

Sum currents:

(4) $$\frac{2.3 - J_4}{1.00} + 2\frac{(460 - J_4)}{11.08} + 2\frac{(J_3 - J_4)}{0.97} = 0$$

$(J_3 = J_6)$

(3) $$\frac{460 - J_3}{1.13} + \frac{460 - J_3}{2.94} + \frac{J_4 - J_3}{0.97} = 0$$

From (4)

$$2.30 - 1.00 J_4 + 83.03 - .181 J_4 + 2.06 J_3 - 2.06 J_4 = 0$$

$$2.06 J_3 - 3.24 J_4 = -85.33$$

From (3) $$407.08 - .885 J_3 + 156.46 - .340 J_3 + 1.03 (J_4 - J_3) = 0$$

$$-2.26 J_3 + 1.03 J_4 = -563.54$$

J3=	367.9882	solution			
J4=	260.3042				
2.06	-3.24		matrix	-85.33	constants
-2.26	1.03			-563.54	
-0.19805	-0.62301				
-0.43457	-0.39611		inverse		

J3= 367.9882 solution
J4= 260.3042

V049-1-033

$$Q_4 = (J_4 - E_{b4}) \Big/ \frac{1-\varepsilon_4}{\varepsilon_4 A_4}$$

$$= (260.3 - 2.3)/1.00$$

$$= 258 \text{ watts}$$

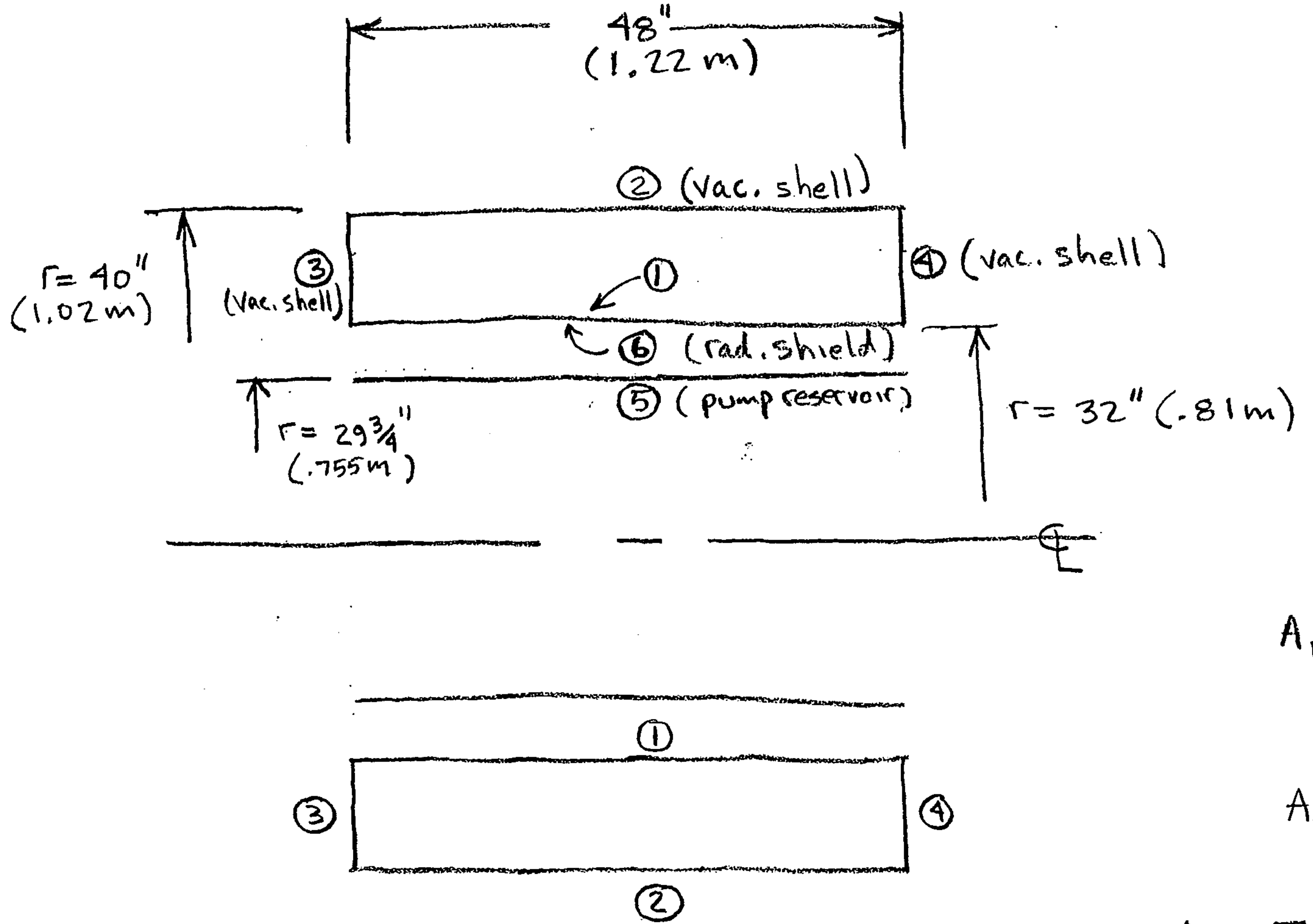
22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

Pump Radiation
Shield Thermal
Calculations

V049-1-033

Short Pump Radiation Shield



$$A_1 = \frac{2\pi(32)(48)}{(39.4)^2} = 6.22\ m^2$$

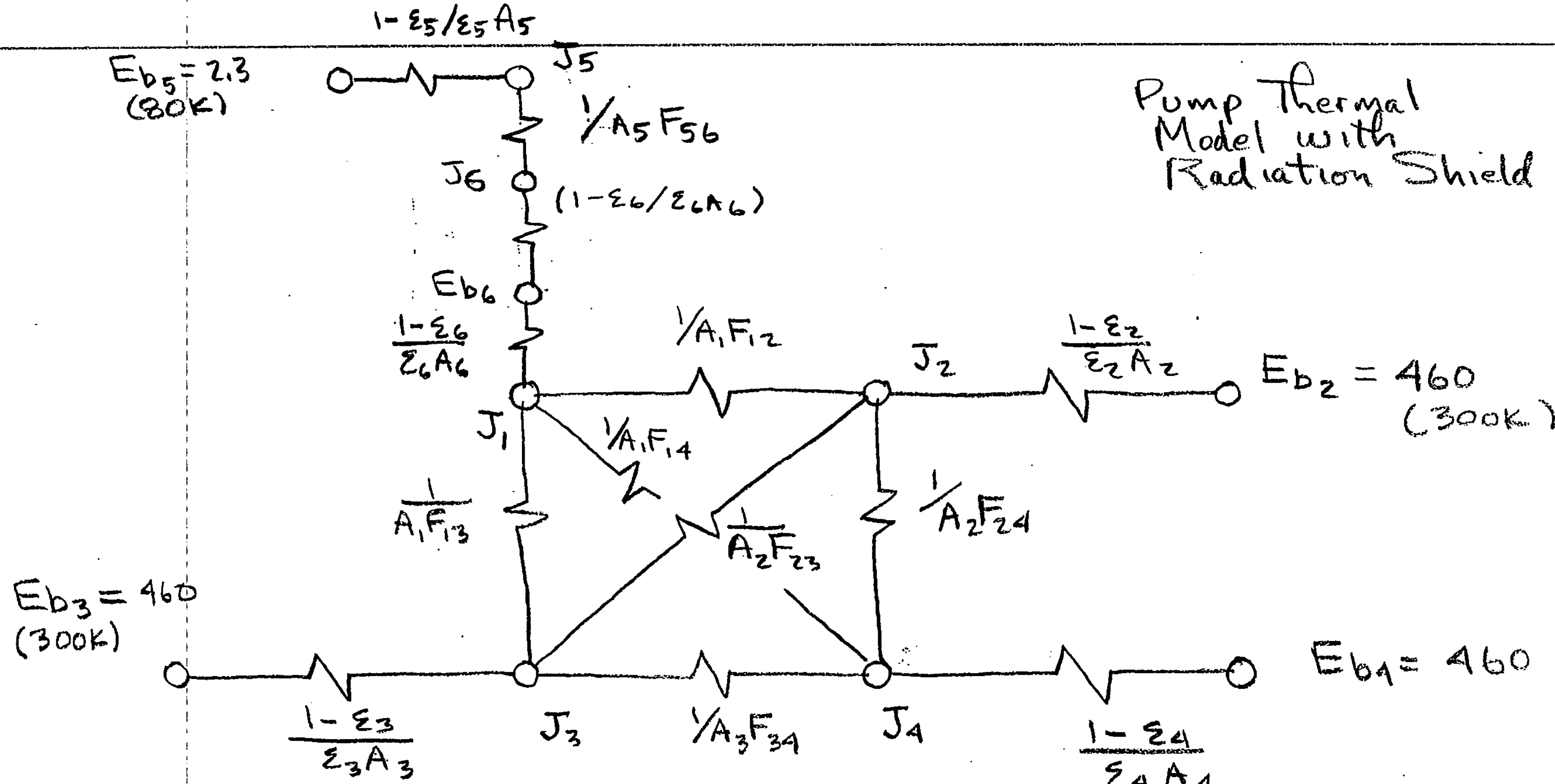
$$A_2 = \frac{2\pi(40)(48)}{(39.4)^2} = 7.77\ m^2$$

$$A_3 = \pi(40^2 - 32^2)/(39.4)^2 = 1.17\ m^2$$

$$A_4 = A_3 = 1.17\ m^2$$

$$A_5 = \frac{2\pi(29.75)(48)}{(39.4)^2} = 5.78\ m^2$$

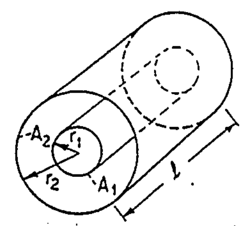
Pump Thermal Model with Radiation Shield



View Factor
Pump Shield to Chamber

(Siegel & Howell)

25



Two concentric cylinders of same finite length.

$R = \frac{r_2}{r_1} \qquad L = \frac{l}{r_1}$

$A = L^2 + R^2 - 1$

$B = L^2 - R^2 + 1$

$$F_{2-1} = \frac{1}{R} - \frac{1}{\pi R}\left\{\cos^{-1}\left(\frac{B}{A}\right) - \frac{1}{2L}\left[\sqrt{(A+2)^2 - (2R)^2}\cos^{-1}\left(\frac{B}{RA}\right) + B\sin^{-1}\left(\frac{1}{R}\right) - \frac{\pi A}{2}\right]\right\}$$

$$F_{2-2} = 1 - \frac{1}{R} + \frac{2}{\pi R}\tan^{-1}\left(\frac{2\sqrt{R^2-1}}{L}\right)$$

$$- \frac{L}{2\pi R}\left\{\frac{\sqrt{4R^2+L^2}}{L}\sin^{-1}\left[\frac{4(R^2-1) + (L^2/R^2)(R^2-2)}{L^2 + 4(R^2-1)}\right]\right.$$

$$\left. - \sin^{-1}\left(\frac{R^2-2}{R^2}\right) + \frac{\pi}{2}\left(\frac{\sqrt{4R^2+L^2}}{L} - 1\right)\right\}$$

where for any argument ξ:

$$-\frac{\pi}{2} \leqslant \sin^{-1}\xi \leqslant \frac{\pi}{2}$$

$$0 \leqslant \cos^{-1}\xi \leqslant \pi$$

Short Pump:

$R = \frac{40''}{32''} = 1.25$

$L = 48/32 = 1.5$

$A = 1.5^2 + 1.25^2 - 1 = 2.81$

$B = 1.5^2 - 1.25^2 + 1 = 1.69$

$\cos^{-1}\left(\frac{B}{A}\right) = .926$

$\cos^{-1}\left(\frac{B}{RA}\right) = 1.069$

$\sin^{-1}\left(\frac{1}{R}\right) = .927$

V049-1-033

$$F_{2-1} = \frac{1}{1.25} - \frac{1}{\pi(1.25)}\left\{.926 - \frac{1}{2(1.5)}\left[\sqrt{4.81^2 - 2.5^2} \times 1.069 + 1.69(.927) - \frac{\pi(2.81)}{2}\right]\right\}$$

$F_{2-1} = .695$ (Results same for long pump)

From view factor algebra

$$A_1 F_{1-2} = A_2 F_{2-1}$$

$$F_{1-2} = \frac{A_2}{A_1} F_{2-1} = \frac{D_2}{D_1} F_{21}$$

$$\therefore F_{1-2} = \left(\frac{80}{64}\right)(.695)$$

$$F_{1-2} = .869$$

F_{2-2} :

$$\tan^{-1}\left(\frac{2\sqrt{1.25^2-1}}{1.5}\right) = .7854$$

$$\sin^{-1}\left(\frac{1.25^2-2}{1.25^2}\right) = -.284$$

$$\frac{\sqrt{4(1.25)^2+(1.5)^2}}{1.5} = 1.944$$

$$\sin^{-1}\left(\frac{4(1.25^2-1) + (1.5^2/1.25^2)(1.25^2-2)}{1.5^2 + 4(1.25^2-1)}\right) = .368$$

$$F_{2-2} = 1 - \frac{1}{1.25} + \frac{2}{\pi(1.25)}(.785)$$

$$- \frac{1.5}{2\pi(1.25)}\left\{ 1.944(.368) - (-.284) + \frac{\pi}{2}(1.302 - 1)\right\}$$

$$F_{2-2} = .318$$

From view factor algebra

$$F_{2-1} + F_{2-2} + F_{2-3} + F_{2-4} = 1.0$$

$$.695 + .318 + 2F_{2-3} = 1.0$$ (Not exactly $= 1.0$ due to round-off error)

$$\therefore F_{2-3} < .01 \quad (\text{use } .01)$$

$$\& \quad F_{2-4} < .01$$

$$\& \quad F_{1-2} + F_{1-3} + F_{1-4} = 1.0$$

$$F_{1-2} + 2F_{1-3} = 1.0$$

$$.869 + 2F_{1-3} = 1.0$$

$$F_{1-3} = .0655$$

$$F_{1-4} = .0655$$

$$A_2 F_{2-3} = A_3 F_{3-2}$$

$$F_{3-2} = \left(\frac{7.77}{1.17}\right)(.01) = .066$$

$$A_1 F_{1-3} = A_3 F_{3-1}$$

$$F_{3-1} = \left(\frac{6.22}{1.17}\right)(.0655) = .348$$

$$F_{3-1} + F_{3-2} + F_{3-4} = 1.0$$

$$\therefore F_{3-4} = .586 \quad \& \quad F_{4-3} = .586 \quad \& \quad F_{1-5} \approx 1.0$$

V049-1-0MM

$E_{b5} = \sigma(80)^4 = 2.3 \ w/m^2$

$E_{b2} = E_{b3} = E_{b4} = \sigma(300)^4 = 460 \ w/m^2$

Unknowns: J_1, J_2, J_3; $J_3 = J_4$ by symmetry
J_6, E_{b6}, J_5

$\frac{1-\varepsilon_5}{\varepsilon_5 A_5} = \frac{1-.06}{.06(5.78)} = 2.710$ $\qquad$ $\frac{1-\varepsilon_3}{\varepsilon_3 A_3} = \frac{1-0.3}{0.3(1.17)} = 1.994$

$\frac{1-\varepsilon_2}{\varepsilon_2 A_2} = \frac{1-0.3}{0.3(7.77)} = 0.300$ $\qquad$ $\frac{1-\varepsilon_4}{\varepsilon_4 A_4} = 1.994$

$\frac{1-\varepsilon_6}{\varepsilon_6 A_6} = \frac{1-.06}{.06(6.22)} = 2.519$

$\frac{1}{A_1 F_{12}} = \frac{1}{6.22(.869)} = .185$ $\qquad$ $\frac{1}{A_1 F_{13}} = \frac{1}{6.22(.0655)} = 2.455$

$\frac{1}{A_2 F_{24}} = \frac{1}{7.77(.01)} = 12.87$ $\qquad$ $\frac{1}{A_1 F_{14}} = \frac{1}{6.22(.0655)} = 2.455$

$\frac{1}{A_2 F_{23}} = \frac{1}{7.77(.01)} = 12.87$ $\qquad$ $\frac{1}{A_3 F_{34}} = \frac{1}{1.17(.586)} = 1.459$

$\frac{1}{A_1 F_{15}} = \frac{1}{6.22(1.0)} = .1608$

$\frac{1}{A_5 F_{56}} = \frac{1}{5.78(1.0)} = .1730$

Sum the currents into the nodes

① J_1 : $$\frac{E_{b6} - J_1}{2.519} + \frac{J_2 - J_1}{.185} + \frac{J_3 - J_1}{2.455} + \frac{J_4 - J_1}{2.455} = 0 \checkmark$$

② J_2 : $$\frac{J_1 - J_2}{.185} + \frac{460 - J_2}{0.300} + \frac{J_3 - J_2}{12.87} + \frac{J_4 - J_2}{12.87} = 0$$

③ J_3 : $$\frac{460 - J_3}{1.994} + \frac{J_1 - J_3}{2.455} + \frac{J_2 - J_3}{12.87} + \cancel{\frac{J_4 - J_3}{1.459}}^{\,0} = 0$$

④ J_4 : $$\frac{460 - J_4}{1.994} + \frac{J_2 - J_4}{12.87} + \frac{J_1 - J_4}{2.455} + \cancel{\frac{J_3 - J_4}{1.459}}^{\,0} = 0$$

(not an independent equation)

⑤ J_5 : $$\frac{2.3 - J_5}{2.710} + \frac{J_6 - J_5}{.1730} = 0$$

⑥ J_6 : $$\frac{J_5 - J_6}{.1730} + \frac{E_{b6} - J_6}{2.519} = 0$$

⑦ E_{b6} : $$\frac{J_6 - E_{b6}}{2.519} + \frac{J_1 - E_{b6}}{2.519} = 0$$

From ① $.397E_{b6} - .397J_1 + 5.405J_2 - 5.405J_1 + .407J_3 - .407J_1$

$+ .407J_3 - .407J_1 = 0$

$.397E_{b6} - 6.618J_1 + 5.405J_2 + .814J_3 = 0$

From ② $5.405J_1 - 5.405J_2 + 1533.33 - 3.333J_2 + .0777J_3$

$- .0777J_2 + .0777J_3 - .0777J_2 = 0$

$5.405J_1 - 8.893J_2 + .1554J_3 = -1533.33$

From ③ $230.692 - .502J_3 + .407J_1 - .407J_3$

$+ .0777J_2 - .0777J_3 = 0$

$.407J_1 + .0777J_2 - .987J_3 = -230.692$

V049-1-033

From ⑤ $\quad .849 - .369 J_5 + 5.78 J_6 - 5.78 J_5 = 0$

$$-6.149 J_5 + 5.78 J_6 = -.849$$

From ⑥ $\quad 5.78 J_5 - 5.78 J_6 + .397 E_{b6} - .397 J_6 = 0$

$$5.78 J_5 - 6.177 J_6 + .397 E_{b6} = 0$$

From ⑦ $\quad .397 J_6 - .397 E_{b6} + .397 J_1 - .397 E_{b6} = 0$

$$.397 J_1 + .397 J_6 - .794 E_{b6} = 0$$

$$\begin{bmatrix} -6.618 & 5.405 & .814 & 0 & 0 & .397 \\ 5.405 & -8.893 & .1554 & 0 & 0 & 0 \\ .407 & .0777 & -.987 & 0 & 0 & 0 \\ 0 & 0 & 0 & -6.149 & 5.78 & 0 \\ 0 & 0 & 0 & 5.78 & -6.177 & .397 \\ .397 & 0 & 0 & 0 & .397 & -.794 \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ J_3 \\ J_5 \\ J_6 \\ E_{b6} \end{bmatrix} = \begin{bmatrix} 0 \\ -1533 \\ -230.692 \\ -.849 \\ 0 \\ 0 \end{bmatrix}$$

-6.618	5.405	0.814	0	0	0.397	0
5.405	-8.893	0.1554	0	0	0	-1533.33
0.407	0.0777	-0.987	0	0	0	-230.692
0	0	0	-6.149	5.78	0	-0.849
0	0	0	5.78	-6.177	0.397	0
0.397	0	0	0	0.397	-0.794	0

-0.37828	-0.23296	-0.34865	-0.12942	-0.137687	-0.25798
-0.23296	-0.25607	-0.23244	-0.0797	-0.084793	-0.15888
-0.17433	-0.11622	-1.17524	-0.05964	-0.063452	-0.11889
-0.12942	-0.0797	-0.11929	-1.8271	-1.770734	-0.95008
-0.13769	-0.08479	-0.1269	-1.77073	-1.883779	-1.01073
-0.25798	-0.15888	-0.23778	-0.95008	-1.010733	-1.8938

(Matrix inversion)

solution

J1=	437.7435
J2=	446.3248
J3=	449.3749
J5=	151.283
J6=	160.7942
Eb6=	299.2688

∴ Heat load on pump reservoir is:

$$\frac{J_5 - E_{b5}}{\left(\frac{1-\varepsilon_5}{\varepsilon_5 A_5}\right)} = \frac{151.28 - 2.3}{2.71}$$

$$= 55 \text{ watts}$$

For long pump the load may be scaled up by the length ratios to give a good approximation

$$\therefore \quad Q_{\substack{\text{Long}\\\text{pump}}} = 55\left(\frac{146''}{48''}\right)$$

$$= 167 \text{ watts}$$

Shield temp $= \left(\frac{299.27}{5.67\times10^{-8}}\right)^{1/4} = 269.5$ K

Calculation of Heat Load From Ends of 80K Pump *

For floating shield, the temperature of the shield was calculated from the computer model of the single pump shield as 269.5 K

Area of ends : $A = \frac{\pi}{4}(D_o^2 - D_i^2) \times 2 \text{ ends}$

$$= \frac{\pi}{4}(57.5^2 - 53^2) \times 2 \times 6.45$$

$$= 5038 \text{ cm}^2$$

$$Q = \sigma A \varepsilon F (T_1^4 - T_2^4)$$

$$= (5.67\times10^{-12})(5038)(.06)((269.5)^4 - (80)^4)$$

$$= \underline{9.0 \text{ watts}}$$

* Ends of pump LN_2 reservoir are shielded from pump vacuum chamber.

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-037
REV.	DEO #	DATE	BY:	CHECK		PAGE 1 OF 7
Ø	0041	1/9/96	D. Moore	D.M.	TITLE: Steady State LN_2 Requirements for 80K Pump and Two Phase Flow Regime Calculations for Supply Line	
1	0056	1/30/96	D. Moore	D.M.		
					By: David Moore	DEPT.: 744

PROJECT: LIGO

PROJECT NO: V59049

PURPOSE: To determine LN_2 consumption for 80K pump & determine supply line size / two phase flow regime

METHOD: Standard methods on a spreadsheet and use of published charts for two phase flow.

ASSUMPTIONS: Steady state conditions

INPUTS: Heat flux calculations

REFERENCES:
1. LIGO doc. # V049-1-033
2. Published charts for two phase flow in vertical & horizontal pipes
3. Nitrogen properties from GASPAK (see pg. 8)

CALCULATIONS: (SEE ATTACHED)

CONCLUSIONS:
1. Short pump consumption: range = .0224 – .0614 gpm
2. Long pump consumption: range = .0479 – .0781 gpm
3. Use 1/2" pipe for supply line. Slug flow unavoidable if supply line downstream of control valve is vertical.

NOTES:

LN2 Requirements for
80K pumps

1/30/96

Heat Load Summary
(watts)

	Short Pump Clean	Short Pump Frosted	Long Pump Clean	Long Pump Frosted
Beam Tube Load	116	499	249	546
Vac. chamber	64	64	176	176
Supports (est.)	9	9	14	14
Pump subtotal	189	572	439	736
VJ pipe (55')	6.06	6.06	6.06	6.06
Valves (3)	12.1	12.1	12.1	12.1
Bayonets	12.39	12.39	12.39	12.39
Supply line subtotal	30.55	30.55	30.55	30.55
Pump & supply line total (watts)	219.55	602.55	469.55	766.55
LN2 Consump. (gpm)				
-pump	0.01926359	0.05830038	0.04474453	0.0750159
-supply line	0.00311377	0.00311377	0.00311377	0.0031138
Total (gpm)	0.02237736	0.06141416	0.0478583	0.0781297

88g/day

112g/day

V049-1-037
Pg 2 of 7

LIGO 80K Pump 1/30/96

Flow Regime in supply line

```
+-----------------+
|Two Phase Flow   |
|Horizontal pipe  |
+-----------------+
```

Pipe dia. 1/2 in. 0.0562 ft.

		Long pump Clean	Long Pump Frosted	Short Pump Clean	Short Pump Frosted
Transf. line heat leak	watts	30.55	30.55	30.55	30.55
Pump heat leak	watts	439	736	189	736
Total heat leak	watts	469.55	766.55	219.55	766.55
Mixture quality		0.11970043	0.09493444	0.19248617	0.10559136
Liquid Flow Rate	gpm	0.0478583	0.0781297	0.02237736	0.06141416
Liquid Flow Rate	lb/min.	0.3206762	0.52351077	0.14994028	0.41150771
Vapor Flow Rate	lb/min.	0.03838508	0.0496992	0.02886143	0.04345166
Liquid density	lb/ft**3	50.12	50.12	50.12	50.12
Vapor density	lb/ft**3	0.3293	0.3293	0.3293	0.3293
Surface tension	dyne/cm	12.26	12.26	12.26	12.26
Liquid viscosity	cp	0.1449	0.1449	0.1449	0.1449
Mixture velocity	ft/sec	0.82636998	1.08446858	0.60911571	0.94194922
Lamdba(flow param.)		1.87943254	1.87943254	1.87943254	1.87943254
Psi(flow param.)		1.100466	1.100466	1.100466	1.100466
Pipe area	ft**2	0.00248	0.00248	0.00248	0.00248
Gf(flow/unit area)	lb/hr -ft**2	7758.29523	12665.5832	3627.58738	9955.83179
Gg(flow/unit area)	lb/hr -ft**2	928.67129	1202.4	698.260403	1051.24984
Gg/lambda		494.123237	639.767576	371.52725	559.344279
Gf(lambda)(Psi)/Gg		17.2785643	21.7861051	10.7449362	19.5873182
Flow Regime		stratified	stratified	stratified	stratified

V049-1-037

Pg 3 of 7

+-----------------+
| Two Phase Flow |
| Vertical pipe |
+-----------------+

Volumetric gas fraction	Fv	0.94796708	0.93527163	0.96699312	0.94142174
Froude No.	NFr	0.37783024	0.65070118	0.20528029	0.49091084
Flow Regime		slug	slug	slug	slug

V049-1-037

Pg 4 of 7

The boundaries between flow regime e not sharp and the pictures used to d ribe th m represent idealized descriptions of a very complex distribution of phases.

Figure 9 shows the flow regimes which have been identified by Baker [6] in a horizontal pipe, and Fig. 10 is the flow regime map. The slug and plug regimes are

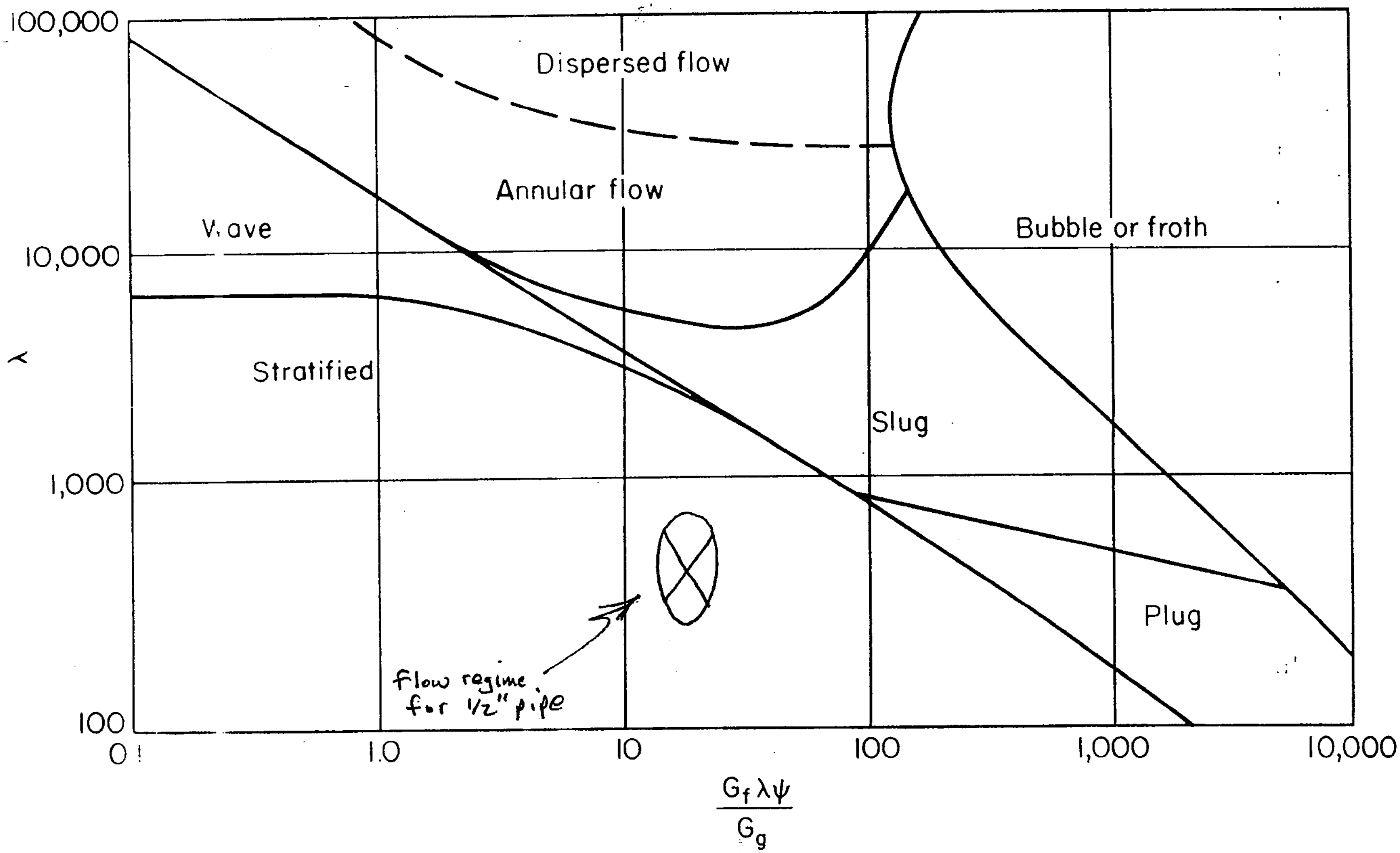
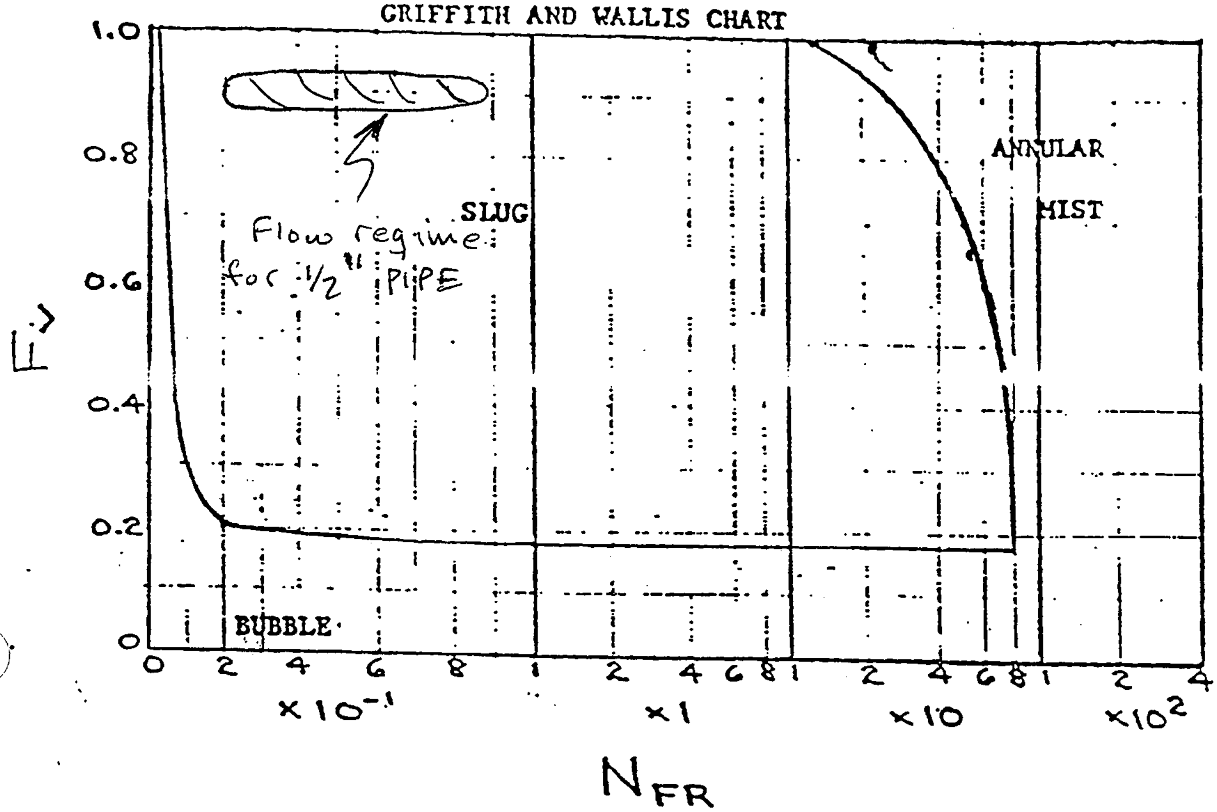


Fig. 10. Flow regime map for a horizontal pipe [6].

V049-1-037
Pg 5 of 7

B) Vertical Lines



Nomenclature:

- Fv = $Q_G/(Q_G + Q_L)$, flowing volumetric gas fraction
- N_{FR} = $\frac{(V_m)^2}{(g_c)(D_p)}$, Froude Number
- Q_G = gas flow, ft^3/sec.
- Q_L = liquid flow, ft^3/sec.
- Vm = $\frac{(Q_G + Q_L)}{(A_p)}$, two phase mixture velocity, ft/sec.
- Ap = cross sectional area of pipe, ft^2
- Dp = diameter of pipe, ft
- gc = gravitational constant, 32.2 ft/sec^2

Nitrogen

```
   INPUT NEW VALUE  ONLY FOR TEMP                INPUT 1
   QUIT                                          INPUT Q
   YOUR CHOICE .............................          P

NAME THE FIRST INPUT VARIABLE
(B BACKS UP ONE STEP, Q STOPS, ? FOR HELP).........  PRESS

NAME THE SECOND INPUT VARIABLE
(B BACKS UP ONE STEP, Q STOPS, ? FOR HELP).......... SAT

INPUT VALUE OF PRESSURE   [PSI]      ........ 29.7

FLUID = NITROGEN
 PRESSURE   TEMP        DENSITY     CP          QUALITY     ENTHALPY    VISC
 [PSI]      [K]         [LB/FT3]    [J/G-K]     [-]         [J/G]       [LBM/FT-S]
  29.70      83.88       48.54       2.088      0.0000      -107.8      0.8097E-04
  29.70      83.88      0.5525       1.179       1.000       81.76      0.3888E-05

DECIDE WHAT TO DO NEXT:
   RETURN TO THE MAIN MENU                       INPUT M
   SELECT NEW INPUT PARAMETERS                   INPUT P
   INPUT NEW VALUE  ONLY FOR PRESSURE            INPUT 1
   QUIT                                          INPUT Q
   YOUR CHOICE .............................

NAME THE SECOND INPUT VARIABLE
(B BACKS UP ONE STEP, Q STOPS, ? FOR HELP).......... ENTHALPY

INPUT VALUE OF PRESSURE   [PSI]      ........ 17

INPUT INITIAL VALUE OF ENTHALPY   [J/G]       -107.8

INPUT ITS INCREMENT (0 FOR ONE POINT)....... 0

FLUID = NITROGEN
 PRESSURE   TEMP        DENSITY     CP          QUALITY     ENTHALPY    VISC
 [PSI]      [K]         [LB/FT3]    [J/G-K]     [-]         [J/G]       [LBM/FT-S]
  17.00      78.62       50.12       2.066      0.0000      -118.8      0.9726E-04
  17.00      78.62       5.313      0.0000      0.5578E-01  -107.8      0.0000
  17.00      78.62      0.3293       1.132       1.000       78.17      0.3613E-05

DECIDE WHAT TO DO NEXT:
   RETURN TO THE MAIN MENU                       INPUT M
   SELECT NEW INPUT PARAMETERS                   INPUT P
   INPUT NEW VALUES FOR BOTH PARAMETERS          INPUT B
   INPUT NEW VALUE  ONLY FOR PRESSURE            INPUT 1
   INPUT NEW VALUES ONLY FOR ENTHALPY            INPUT 2
   QUIT                                          INPUT Q
   YOUR CHOICE .............................
```

V049-1-037

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-072 PAGE 1 OF 15
REV.	DEO #	DATE	BY:	CHECK	TITLE: 80K Pump Roughdown ΔP Analyses	
0		3/19/96	DM	R. Thar.		
					BY: David Moore	DEPT.: 744

PROJECT: LIGO

PROJECT NO: V59049

PURPOSE: Determine if any significant pressure differential exists across the 5/16" gap separating the low e liner and the thermal radiation shield in the 80K pump during pumpdown which could structurally damage either of these components.

METHOD: Computer simulation of the roughdown of the 80K pump chamber volume. The computer program is a finite difference code which utilizes the Newton- Raphson method to solve the system equations.

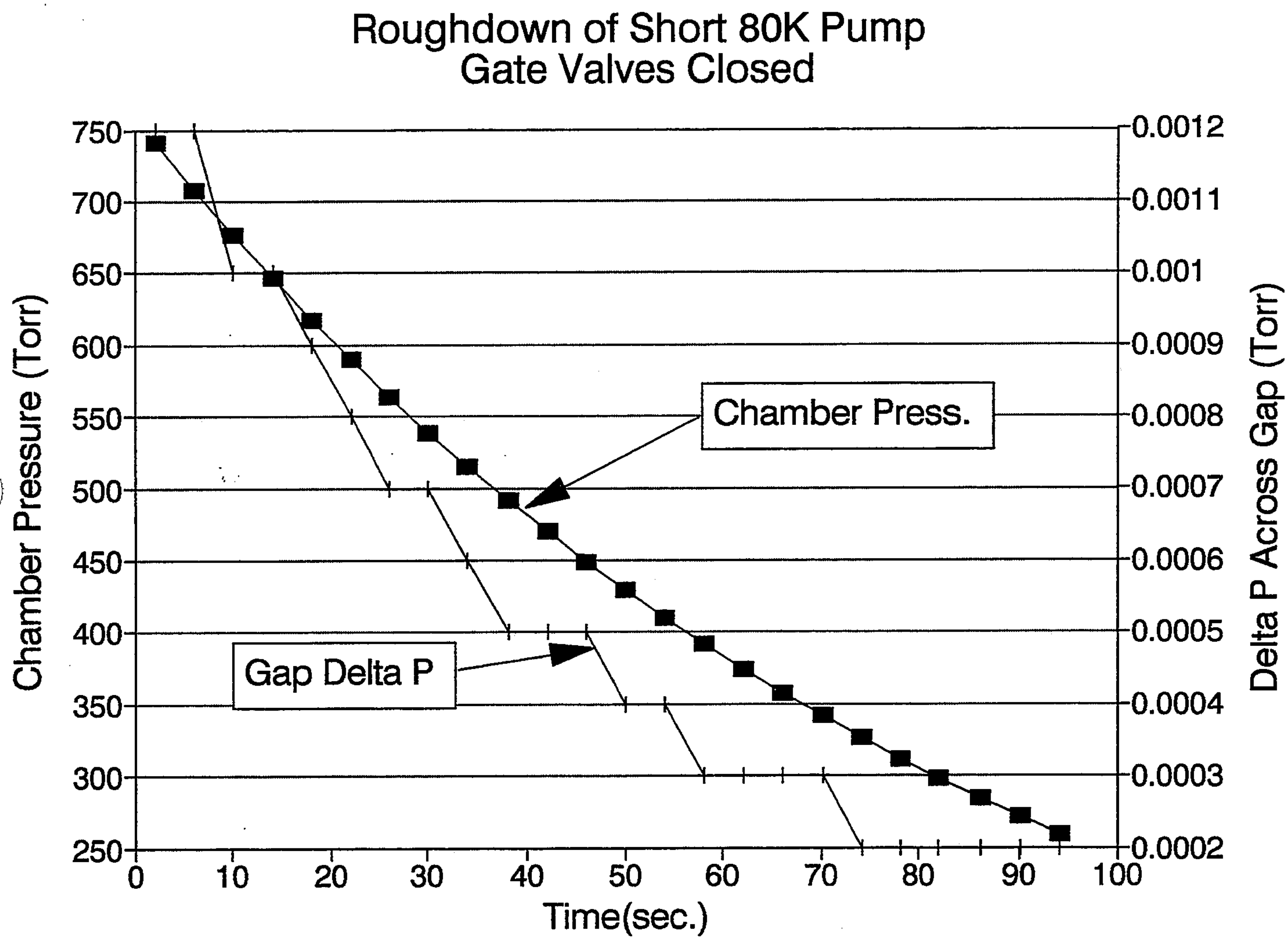
ASSUMPTIONS: The gap which separates the low e liner and the radiation shield is modelled as a short pipe of equivalent diameter with entrance and exit losses equal to 1.5 velocity heads. The roughing process is assumed to be executed with the turbo backing pump, whose speed (90 cu. m./hr.) is approximately constant during the pressure range of interest.

INPUTS: Input file attached.

REFERENCES:

CALCULATIONS: Related calculations attached.

CONCLUSIONS: Delta P across the gap is insignificant. No significant structural loads.


Roughdown of Short 80K Pump
Gate Valves Closed
Chamber Press.
Gap Delta P
Chamber Pressure (Torr)
Delta P Across Gap (Torr)
Time(sec.)
750
700
650
600
550
500
450
400
350
300
250
0.0012
0.0011
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0
10
20
30
40
50
60
70
80
90
100

```
 FLUID BCD 3GENERAL
       BCD 9  PRESS. VS TIME IN 80K PUMP CHAMBER
       BCD 9  ROUGHDOWN CHAMBER WITH TURBO BACKING PUMP
       END
       BCD 3PRESSURE DATA
       REM   NODE #, ELEVATION, INIT PRESS;  ETC.
           -1,         0.,      760.$
           5,          0.,      760.$
           10,          0.,      760.$
           9999,       0.,      1.0 $ DUMMY PRESSURE NODE
       END
       BCD 3TUBE DATA
C    ABS  TUBE #, INIT NODE, TERM NODE, A(REF #, ARRAY DATA)
       TUB 10,         1,         5,        A1,     0.0$
       TUB 30,         1,         5,        A1,     0.0$
       PMI -20,        5,         10,       A5,     0.0$
       END
       BCD 3CONSTANTS DATA
           GRAV=32.2 $
           GC1=89.6606 $CONVERSION TO TORR
           GC2=1.0 $
           USRFLO=0.1 $
C          SPARE6 = 0. (1.) CAUSES "DEBUG" TO BE .FALSE. (.TRUE.).
           SPARE6 = 1. $
C          SPARE7 = 0. (1.) CAUSES "NOFERR" TO BE .FALSE. (.TRUE.).
           SPARE7 = 1. $
C          THE FOLLOWING LINE CAUSES ORDER REDUCTION TO BE SUPRESSED.
           ISOLVE = 2
C          THE FOLLOWING PARAMETERS CONTROL CONVERGENCE FOR THE FLUID
           NETWORK SOLUTION AND OVERRIDE THE DEFAULT VALUES ...
           KMAX=100 $
           PRSABS=0.001 $
           PRSREL=0.001 $
           FLOABS=0.0001 $
           FLOREL=0.0001 $
           NDIM=10000$
           NFLOOP= 10
           PRLXCA= 0.001
           EPS=0.01
           PMPTOL=0.005
           1=0.0         $ TOTAL MASS OUTFLOW, OUTER CHAM. VOLUME
           5=0.0         $ TOTAL MASS OUTFLOW, INNER CHAM. VOLUME
           10=760.       $ PRESSURE IN OUTER CHAM. VOLUME (TORR)
           50=760.       $ PRESSURE IN INNER CHAM. VOLUME (TORR)
           60=0.         $ DELTA P
           100= 0.0      $ ELAPSED TIME
           200= .0662      $ PUMP FLOW
           1000=2627.    $ INITIAL AIR MASS, OUTER CHAM. VOLUME, GM.
           2=16.0         $ TIME COUNTER
           3=.075         $ INITIAL AIR DENSITY
           6=.125         $ TIME STEP (SEC.)
      END
      BCD 3ARRAY DATA
      REM        L  ,    D  , K  ,    E/D  , FIVE EMPTY FIELDS
           1,.125, .624,  1.50, .00018, 0.0, 0.0, 0.0, 0.0, 0.0, END$ANNULUS
C--- PUMP CHARACTERISTICS
C--- MASS FLOW RATE VS.(DOWNSTREAM - UPSTREAM PRESS.)
           5,.0,15.,1.0,15., END
C--- PUMP DOWN CURVE
           7,4.,.0004,13.,.0011,22.,.0019,27.,.0024,34.,.0030
```

V049-1-072
Pg 3 of 15

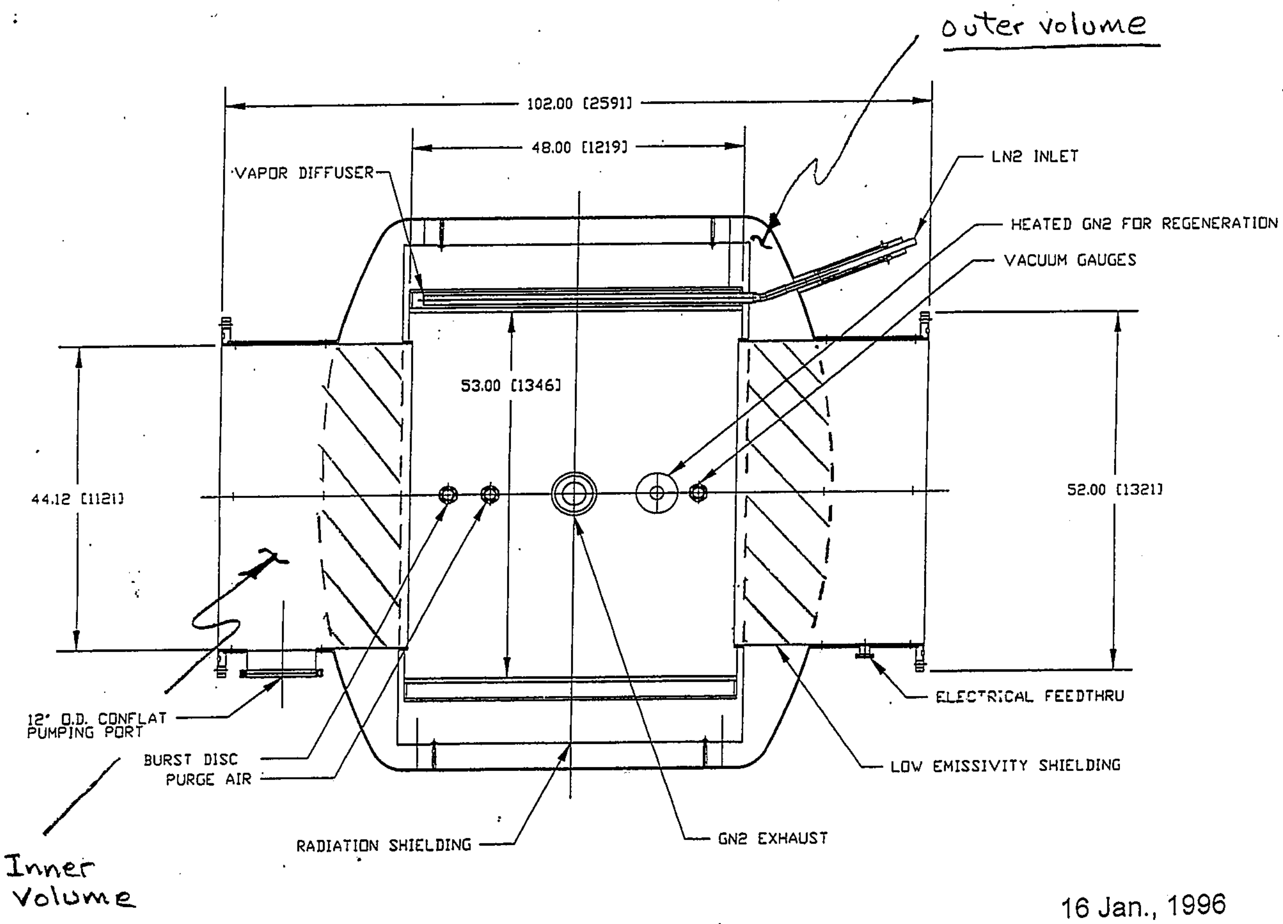
```
               43.,.0037,53.,.0047,67.,.0058,85.,.0073
               135.,.0117,170.,.0149,220.,.0190,355.,.0310
               460.,.0398,590.,.0512,760.,.0662,END
        END
        BCD 3EXECUTION
C---- OBTAIN PUMP MASS FLOW FROM CHAMBER PRESSURE
            D1DEG1(XK10,A7,XK200)
F      OPEN(UNIT=7,FILE='PRESS.OUT',ACCESS='SEQUENTIAL',
F     +    STATUS='OLD',FORM='FORMATTED')
F      WRITE(7,50)
F   50 FORMAT(5X,'TIME(SEC)',5X,
F     +      'DP(TORR)',1X,'P1(TORR)',/)
F 100 CONTINUE
C---- SET PUMP MASS FLOW
M      W20=XK200
F      CONTINUE
            FLDSOL
F      CALL PMPFLO
M      IF(P1.GE.250.0)THEN
F      CONTINUE
M       IF(XK2.LE.0.)THEN
F        CALL DATPRT
F 105       CONTINUE
F       END IF
M      XK2=XK2-1.0
F       GO TO 100
F      ELSE
F       CONTINUE
F      END IF
       CLOSE(UNIT=7)
        END
        BCD 3VARIABLES F

        REM  DYNAMIC VISCOSITY UNITS = LBM/FT-SEC
            TUBE(10,.0000123,K3,80.)
C            TUBE(20,.0000123,K3,80.)
            TUBE(30,.0000123,K3,80.)
        END
        BCD 3VARIABLES 1
        END
        BCD 3VARIABLES 2
        END
        BCD 3OUTPUT CALLS
M      IF(XK2.LE.0.)THEN
F        CALL PPRINT
F        CALL WPRINT
F      ELSE
F        CONTINUE
F      END IF
CM      IF(XK60.GE.2.0)THEN
CM       WRITE(7,800)XK100,XK60,P1
CM      ELSE
CM       CONTINUE
CM      END IF
F 800   FORMAT(5X,',',F9.2,',',F8.2,',',F8.2)
        END
        BCD 3SINROUTINE PMPFLO
C---- COMPUTE MASS OUTFLOW DURING SELECTED TIME STEP
M       XK1=(W10+W30)*XK6*453.6
M       XK5=W20*XK6*453.6
```

V049-1-072
Pg 4 of 15

```
C---- COMPUTE DELTA P ACROSS GAP
M      XK60=ABS(P5-P1)
C---- COMPUTE NEW PRESSURE IN CHAMBER OUTER VOLUME
C
C---- OUTER VOLUME
M        XK10=.289*(XK1000-XK1)
M        P1=XK10
C
C---- COMPUTE ELAPSED TIME
M        XK100=XK100+XK6
C---- COMPUTE REMAINING AIR MASS
M        XK1000=XK1000-XK1
CM        XK5000=XK5000-XK5
C--- COMPUTE AIR DENSITY
M      XK3=XK1000/34926.
C----- UPDATE PUMP FLOW RATE
           D1DEG1(XK10,A7,XK200)
M      W20=XK200
C
        END
        BCD 3SINROUTINE DATPRT
M      IF(XK2.LE.0.)THEN
M       XK2=16.0
F      END IF
M        WRITE(6,200)XK1,XK5
M        WRITE(6,300)XK100
M        WRITE(6,400)XK1000
M        WRITE(6,700)XK10
M        WRITE(6,600)XK200
M        WRITE(6,980)XK3
M        WRITE(7,800)XK100,XK60,P1
M        CONTINUE
C
F 200    FORMAT(/,5X,'MASS OUTFLOW FROM OUTER VOL.= ',F10.4,' GRAMS',
F    +          /,5X,'MASS OUTFLOW FROM INNER VOL.= ',F10.4,' GRAMS',/)
F 300    FORMAT(5X,'ELAPSED TIME = ',F10.3,' SEC.')
F 400    FORMAT(5X,'REMAINING MASS,OUTER CHAM.= ', F10.2,' GRAMS')
F 500    FORMAT(5X,'REMAINING MASS,INNER CHAM.= ', F10.2,' GRAMS')
F 600    FORMAT(/,5X,'PUMPFLOW= ',F10.4,' LBM/SEC')
F 700    FORMAT(/,5X,'OUTER CHAMBER PRESS= ',F10.4)
F 800    FORMAT(5X,',',F9.2,',',F10.4,',',F8.2)
F 980    FORMAT(5X,'AIR DENSITY= ',F6.4,1X,'LBM/FT^^3')
        END
        BCD 3END OF DATA
```

Appendix
(Related Calculations)

Pumpdown of 80K
Pump Chamber
(Small Chamber)



16 Jan., 1996

PLAN VIEW

Calculation of Volumes

Calculate the outer chamber volume (ref: sketch) by calculating the gross chamber volume bounded by the chamber shell & heads, & subracting out the volume inside the thermal radiation shield & the cross-hatched volume in the sketch:

Shell: $V = \frac{\pi d^2}{4} \times \text{length}$

$$= \frac{\pi (79\tfrac{1}{2})^2}{4} (48)$$

$$= 238{,}147 \text{ in}^3 \ (3.89 \ m^3)$$

Heads:

Volume of elliptically dished head is approximated by:

$$V = 7.6 \times 10^{-5} d_i^{\,3}$$

d_i: in.
V: ft^3

$$\therefore V = 7.6 \times 10^{-5} (79\tfrac{1}{2})^3$$

$$= 38.19 \ ft^3$$

For 2 heads, $76.37 \ ft^3$ ($2.16 \ m^3$)

∴ Gross chamber volume (excluding the protruding beam ports) is:

$$\begin{array}{r} 2.16 \\ +\ 3.89 \\ \hline 6.05 \ m^3 \end{array}$$

Volume inside the radiation shield:

$$V = \frac{\pi}{4} d^2 \times \text{length}$$

$$= \frac{\pi}{4} (72)^2 \times (50)$$

$$= 203{,}472 \text{ in}^3 \quad (3.33 \text{ m}^3)$$

Volume inside cross-hatched volume:

Approximate as cylinders $44\frac{1}{8}$" dia. x $10\frac{3}{4}$" high

$$\therefore \text{Vol} = 2 \times \frac{\pi}{4} d^2 \times \text{length}$$

$$= 2\left(\frac{\pi}{4}\right)\left(44\tfrac{1}{8}\right)^2\left(10\tfrac{3}{4}\right)$$

$$= 32877 \text{ in}^3 \quad (.54 \text{ m}^3)$$

$\therefore$ Outerchamber volume is

$$6.05 - (3.33 + .54) = 2.18 \text{ m}^3$$

//

The inner volume to be evacuated is the volume between closed gate valves. This includes the volume inside the radiation shield, the beam tube ports, and the spool piece on one end of the pump.

Beam tube ports:

$$V = 2 \times \frac{\pi d_i^2}{4} \times \text{length}$$

$$= 2\left(\frac{\pi}{4}\right)\left(44\tfrac{1}{8}\right)^2\left(26\tfrac{1}{4}\right)$$

$$= 80282 \text{ in}^3 \quad (1.31 \text{ m}^3)$$

Spool piece:

$$V = \frac{\pi}{4}\left(44\tfrac{5}{8}\right)^2(36)$$

$$= 56277 \text{ in}^3 \quad (.92 \text{ m}^3)$$

$\therefore$ Total inner volume is:

$$3.33 + 1.31 + .92 = 5.56 \text{ m}^3$$

Mass of air in chamber:

Outer chamber volume initial air mass:

$$V = 2.18\ m^3$$

$$m = \rho V = 2.18\ m^3 \left(2.65\ \frac{lbm}{m^3}\right)$$
$$= 5.79\ lbm\ (2627\ gm.)$$

Inner volume:

$$V = 5.56\ m^3$$
$$m = 5.56(2.65)$$
$$= 14.73\ lbm\ (6689\ gm.)$$

Computations for computer simulation:

Density: $\rho = \frac{m}{V}$

For the outer chamber volume

$$\rho = XK1000/2180 \quad gm./Liter$$

or $\rho = \left(\frac{XK1000}{2180}\ \frac{gm}{Liter}\right)\left(\frac{Liter}{.03532\ ft^3}\right)\left(\frac{lbm}{453.6\ gm}\right)$

$$\rho = \left(\frac{XK1000}{34926}\right)\ \frac{lbm}{ft^3}$$

Pressure computation

$$P = \frac{m \bar{R} T}{V M}$$

$M = 28.97 \frac{gm}{mole}$

$\bar{R} = 62.36 \frac{torr\text{-}l}{mole\text{-}K}$

$$P = \frac{m (62.36)(293)}{V (28.97)}$$

$$P = 630.703 (m/V)$$

∴ Outer volume ;

$$P = 630.703 (m/2180)$$

$$\therefore \quad P = .289 m \text{ torr}$$

Inner volume :

$$P = 630.703 (m/5560)$$

$$= .113 m \text{ torr}$$

V049-1-072
Pg 12 of 15

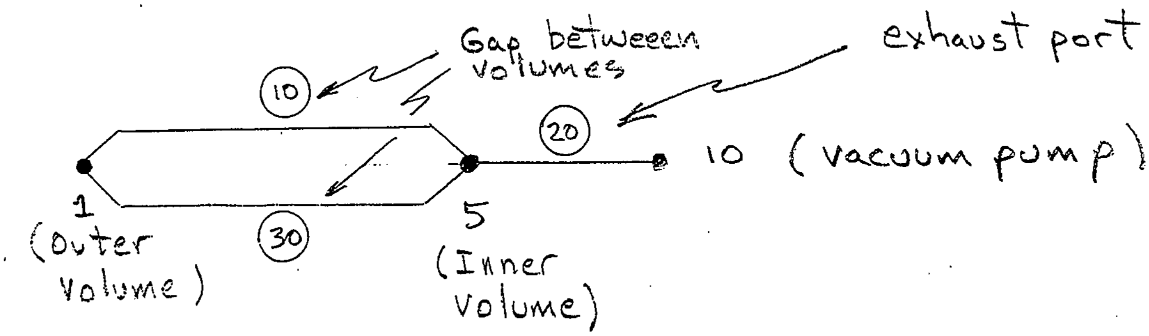
Turbo Backing Pump Curve

Pump has an approximately constant speed ($90\ m^3/hr$) for the pressures of interest.

Pressure (Torr)	S (acfm)	ρ (lbm/ft^3)	$\dot{m}$ (lbm/sec)
760	53.0	.0749	.0662
590		.0580	.0512
460		.0451	.0398
355		.0351	.0310
220		.0215	.0190
170		.0169	.0149
135		.0133	.0117
85		.0083	.0073
67		.0066	.0058
53		.0053	.0047
43		.0042	.0037
34		.0034	.0030
27		.0027	.0024
22		.0022	.0019
13		.0013	.0011
4		.0004	.0004

Pumpdown of
80K Pump Chamber

Fluid Flow Model:



80 K Cryopump
Annular Gap

For performance considerations, the annular gap area should be as large as the turbo inlet port (10" i.d.)

For one gap:

$$\frac{A}{2} = \frac{\pi}{4}\left(D_o^2 - D_i^2\right) \qquad \text{(Area of one gap} = \tfrac{1}{2} \text{ total)}$$

Di defined by low e shield (44.62")

$$\frac{1}{2} \times \cancel{\frac{\pi}{4}}(10^2) = \cancel{\frac{\pi}{4}}\left(D_o^2 - 44.62^2\right)$$

$$D_o = 45.18'' \quad \text{say } 45\tfrac{1}{4}''$$

$$\therefore \text{Gap} = \left(45\tfrac{1}{4} - 44\tfrac{5}{8}\right)/2$$

$$= .3125 \quad (5/16'')$$

The equivalent pipe diameter of a 5/16" gap is

$$\frac{\pi}{4}\left(45\tfrac{1}{4}^2 - 44\tfrac{5}{8}^2\right) = \frac{\pi}{4} d_{equiv}^2$$

$$d_{equiv} = 7.49''$$

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-092 PAGE 1 OF 4
REV.	DEO #	DATE	BY:	CHECK	TITLE: Pressure Drop Calculations for 80K Pump Lines	
Ø	Ø122	4/12/96	D Moore	R. Thom.		
					BY: D. Moore	DEPT.:744

PROJECT: LIGO	PROJECT NO: V59049

PURPOSE: To determine if regeneration and GN2 vent lines are adequately sized for the intended service.

METHOD: Use of in-house computer program for pressure drop analysis.

ASSUMPTIONS: 1) The length of each of the lines are equivalent to 60 ft. of straight pipe.
2) Regen. flow rate is 100 gm./sec.

INPUTS: Regen. heater delta p = .35 psid max. (vendor data)
Vaporizer delta p = 2 psid (budget imposed on vendor)
Estimated Cv for 1-1/2" globe valve in regen line = 31.66

REFERENCES:

CALCULATIONS: Calculations performed for :
Case 1) 80K pump normal operation (long pump, frosted)
Case 2) Long 80K pump cooldown from 150C (423K)
Case 3) Regen of Long 80K pump.

CONCLUSIONS: Case 1): Delta p = .0017 psid for 1-1/2 in. vent line.
Case 2): Delta p = .1392 psid for 1-1/2 in. vent line.
Case 3): Delta p = 9.413 psid from LN2 dewar to exit of vent line.
(by inspection, the 80K short pump system is adequate for 50 gm/sec.)
Conclusion: The lines are adequately sized for their intended service.

PROCESS SYSTEMS INTERNATIONAL, INC   20 Walkup Drive, Westborough, MA 01581

CUSTOMER: LIGO   JOB NO:V59049

PRESSURE DROP ROUTE OR LINE ID:GN2 VENT, NORMAL OP.

PRESSURE:	101270.8 Pa	14.684 PSIA
TEMPERATURE:	77.778 K	140.000 R
DENSITY :	4.581 KG/M^3	0.29 LBS/FT^3
QUALITY :	1.000	

ITEMNAME	FLOWRATE LB/S	I.D. INCHES	K / DO	CV	LENGTH FT	PRESSURE PSIA	Z1 FEET	Z2 FEET	DP-F PSI	DP-Z PSI	DP-T PSI	DP-SUM PSI
1.5" PIPE	0.0096	1.6820			6.00	14.684	0.00	0.00	0.00017	0.0000	0.0002	0.0002
1.5" PIPE	0.0096	1.6820			6.00	14.684	0.00	0.00	0.00017	0.0000	0.0002	0.0003
1.5" PIPE	0.0096	1.6820			6.00	14.684	0.00	0.00	0.00017	0.0000	0.0002	0.0005
1.5" PIPE	0.0096	1.6820			6.00	14.684	0.00	0.00	0.00017	0.0000	0.0002	0.0007
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0008
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0010
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0012
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0014
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0015
1.5" PIPE	0.0096	1.6820			6.00	14.683	0.00	0.00	0.00017	0.0000	0.0002	0.0017
								TOTAL	0.0017	0.0000		0.0017

BLOWER SUCTION DENSITY: 4.581 KG/M^3   0.286 LB/FT^3

V049-1-092
Pg 2 of 4

PROCESS SYSTEMS INTERNATIONAL, INC 20 Walkup Drive, Westborough, MA 01581

CUSTOMER: LIGO JOB NO:V59049

PRESSURE DROP ROUTE OR LINE ID:GN2 VENT, COOLDOWN FROM 423K

PRESSURE:	101270.8 Pa	14.684 PSIA
TEMPERATURE:	77.778 K	140.000 R
DENSITY :	4.581 KG/M^3	0.29 LBS/FT^3
QUALITY :	1.000	

ITEMNAME	FLOWRATE LB/S	I.D. INCHES	K / DO	CV	LENGTH FT	PRESSURE PSIA	Z1 FEET	Z2 FEET	DP-F PSI	DP-Z PSI	DP-T PSI	DP-SUM PSI
1.5" PIPE	0.0983	1.6820			6.00	14.670	0.00	0.00	0.01386	0.0000	0.0139	0.0139
1.5" PIPE	0.0983	1.6820			6.00	14.657	0.00	0.00	0.01387	0.0000	0.0139	0.0277
1.5" PIPE	0.0983	1.6820			6.00	14.643	0.00	0.00	0.01389	0.0000	0.0139	0.0416
1.5" PIPE	0.0983	1.6820			6.00	14.629	0.00	0.00	0.01390	0.0000	0.0139	0.0555
1.5" PIPE	0.0983	1.6820			6.00	14.615	0.00	0.00	0.01391	0.0000	0.0139	0.0694
1.5" PIPE	0.0983	1.6820			6.00	14.601	0.00	0.00	0.01393	0.0000	0.0139	0.0834
1.5" PIPE	0.0983	1.6820			6.00	14.587	0.00	0.00	0.01394	0.0000	0.0139	0.0973
1.5" PIPE	0.0983	1.6820			6.00	14.573	0.00	0.00	0.01396	0.0000	0.0140	0.1113
1.5" PIPE	0.0983	1.6820			6.00	14.559	0.00	0.00	0.01397	0.0000	0.0140	0.1252
1.5" PIPE	0.0983	1.6820			6.00	14.545	0.00	0.00	0.01398	0.0000	0.0140	0.1392
								TOTAL	0.1392	0.0000		0.1392

BLOWER SUCTION DENSITY: 4.536 KG/M^3 0.283 LB/FT^3

V049-1-092
Pg 3 of 4

PROCESS SYSTEMS INTERNATIONAL, INC   20 Walkup Drive, Westborough, MA 01581

CUSTOMER: LIGO

JOB NO:V59049

PRESSURE DROP ROUTE OR LINE ID:REGEN PUMP TO 423K(300F), VAPORIZER TO VENT 100 GM/SEC.

PRESSURE:	156520.5 Pa	22.695 PSIA
TEMPERATURE:	423.000 K	761.400 R
DENSITY :	1.246 KG/M^3	0.08 LBS/FT^3
QUALITY :	1.000	

ITEMNAME	FLOWRATE LB/S	I.D. INCHES	K / DO	CV	LENGTH FT	PRESSURE PSIA	Z1 FEET	Z2 FEET	DP-F PSI	DP-Z PSI	DP-T PSI	DP-SUM PSI
VAPORIZER	0.2203	1.6820				20.695	0.00	0.00	2.00000	0.0000	2.0000	2.0000
1.5" GLOBE	0.2203	1.6820		31.660		18.5	0.00	0.00	2.22355	0.0000	2.2236	4.2236
1.5" PIPE	0.2203	1.6820			10.00	17.926	0.00	0.00	0.54589	0.0000	0.5459	4.7694
HEATER	0.2203	6.0000				17.576	0.00	0.00	0.35000	0.0000	0.3500	5.1194
3.0" PIPE	0.2203	3.2600			6.00	17.564	0.00	0.00	0.01247	0.0000	0.0125	5.1319
3.0" PIPE	0.2203	3.2600			6.00	17.551	0.00	0.00	0.01247	0.0000	0.0125	5.1444
3.0" PIPE	0.2203	3.2600			6.00	17.539	0.00	0.00	0.01248	0.0000	0.0125	5.1569
3.0" PIPE	0.2203	3.2600			6.00	17.526	0.00	0.00	0.01249	0.0000	0.0125	5.1694
3.0" PIPE	0.2203	3.2600			6.00	17.514	0.00	0.00	0.01250	0.0000	0.0125	5.1819
3.0" PIPE	0.2203	3.2600			6.00	17.501	0.00	0.00	0.01251	0.0000	0.0125	5.1944
3.0" PIPE	0.2203	3.2600			6.00	17.489	0.00	0.00	0.01252	0.0000	0.0125	5.2069
3.0" PIPE	0.2203	3.2600			6.00	17.476	0.00	0.00	0.01253	0.0000	0.0125	5.2194
3.0" PIPE	0.2203	3.2600			6.00	17.464	0.00	0.00	0.01254	0.0000	0.0125	5.2320
3.0" PIPE	0.2203	3.2600			6.00	17.451	0.00	0.00	0.01255	0.0000	0.0125	5.2445
80K PUMP	0.2203	0.0000				17.201	0.00	0.00	0.25000	0.0000	0.2500	5.4945
1.5" PIPE	0.2203	1.6820			6.00	16.849	0.00	0.00	0.35172	0.0000	0.3517	5.8462
1.5" PIPE	0.2203	1.6820			6.00	16.490	0.00	0.00	0.35906	0.0000	0.3591	6.2053
1.5" PIPE	0.2203	1.6820			6.00	16.123	0.00	0.00	0.36688	0.0000	0.3669	6.5722
1.5" PIPE	0.2203	1.6820			6.00	15.748	0.00	0.00	0.37522	0.0000	0.3752	6.9474
1.5" PIPE	0.2203	1.6820			6.00	15.364	0.00	0.00	0.38416	0.0000	0.3842	7.3315
1.5" PIPE	0.2203	1.6820			6.00	14.970	0.00	0.00	0.39376	0.0000	0.3938	7.7253
1.5" PIPE	0.2203	1.6820			6.00	14.566	0.00	0.00	0.40411	0.0000	0.4041	8.1294
1.5" PIPE	0.2203	1.6820			6.00	14.151	0.00	0.00	0.41532	0.0000	0.4153	8.5447
1.5" PIPE	0.2203	1.6820			6.00	13.723	0.00	0.00	0.42750	0.0000	0.4275	8.9722
1.5" PIPE	0.2203	1.6820			6.00	13.282	0.00	0.00	0.44082	0.0000	0.4408	9.4130
							TOTAL		9.4130	0.0000		9.4130

BLOWER SUCTION DENSITY: 0.730 KG/M^3   0.046 LB/FT^3

V049-1-092
Pg 4 of 4

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA	ENGINEERING CALCULATIONS	NO: V049-1-094 PAGE 1 OF 15

REV.	DEO #	DATE	BY:	CHECK
Ø	Ø124	4/19/96	D Moore	D.M.W
1	Ø3Ø7	10/15/96	D Moore	D.M.W

TITLE: Relieving requirements for 80K pump vacuum shell relief device.

BY: D.Moore | DEPT.: 744

PROJECT: LIGO | PROJECT NO: V59049

PURPOSE: To determine the relieving requirements for the vacuum shell of the 80K pump so that in the event of a failure of the 80K pump reservoir, the vacuum shell and the large gate valves in the beam tube are protected from overpressure.

METHOD: Standard thermodynamic and heat transfer analyses, and the use of standard API formula for sizing relief valve orifice.

ASSUMPTIONS: See calculations

INPUTS: Maximum delta p allowed, 1.75 atm., is based on highest pressure differential the large gate valves were designed for.

REFERENCES API 520

CALCULATIONS: See attached.

CONCLUSIONS: Relieving device should be sized to handle a flow rate of 6524 lbm/hr for the set pressure. This requires an orifice size of 3.36 sq. in.

REVISION HISTORY

Rev. 0 Original Issue - April 19, 1996

Rev. 1 Issue Date - Oct. 15, 1996

- Revised sizing of burst disc to take pressue drop of vent line into account. Relieving area increased to 3.36 sq. in.

Cases to consider for sizing relief device:

1. Leak in the LN_2 reservoir cools the entire pump vacuum shell to 80K. Control valve is sized for approx. 9 lbm/hr., so it plays no significant role in this case.

2. Catastrophic rupture of LN_2 reservoir dumps entire liquid inventory at the bottom of the vacuum shell. Vent presumed blocked with ice.

3. LN_2 reservoir ruptures during cooldown. Manual cooldown valve is 100% open. GN_2 vent is open, since it will not have had sufficient time to ice up, and ∴ provides another relieving path. This case less severe than first two cases.

4. LN_2 reservoir ruptures during regen. cycle when pump is warming up. No liquid in reservoir. Max flow for regen is 10600 SCFH (~800 lbm/hr). This case is less severe than the first 2 cases

Case 1 : A leak in the LN_2 reservoir cools the entire vacuum chamber shell to 80K (highly unlikely). Heat is then transferred from the environment to the shell. The relieving device must then pass the following flow rate (see analysis, Attachment 1):

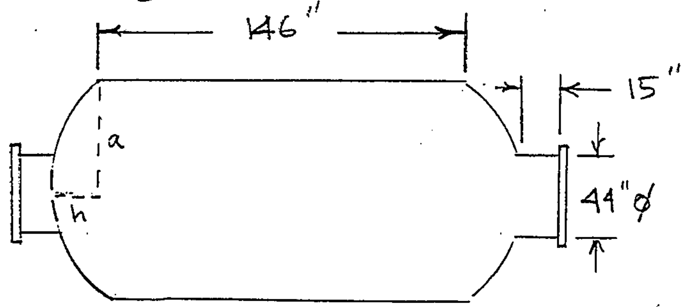
$$\dot{m} = \frac{Q\beta}{c_p}$$

Q = heat transferred from environment to cold vacuum shell.

c_p = specific heat of N_2

β = volume coefficient of expansion

Approximate Surface Area:
(Long Pump)



$a = 40''$

$h \approx 12\frac{1}{2}''$

Cylinder area $= \pi(80)(146) = 36{,}694 \text{ in}^2$

Ports: area $= 2(\pi)(44)(15) = 4147 \text{ in}^2$

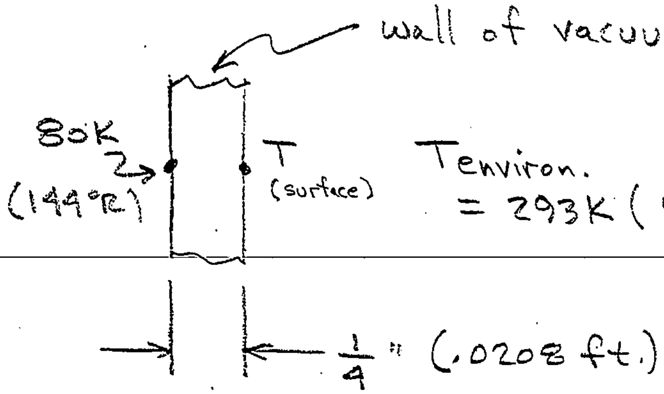
Dished heads:

$$A = 2 \times \pi(a^2 + h^2)$$
$$= 2\pi\left(40^2 + (12\tfrac{1}{2})^2\right)$$
$$= 11035 \text{ in}^2$$

Total:

$$\begin{array}{r} 36694 \\ 4147 \\ 11035 \\ \hline 51876 \end{array} \text{ in}^2 \quad (3.346 \times 10^5 \text{ cm}^2)$$

Heat transferred to cold shell (per unit area):



$T_{environ.} = 293K\ (527°R)$

Energy balance:

$$\frac{kA}{t}(T-144) = hA(527-T) + \sigma A \varepsilon (527^4 - T^4)$$

$A = 1.0\ ft^2$

$\varepsilon = 1.0$

& $h = 0.27\left(\frac{\Delta T}{d}\right)^{1/4}$

d = dia of cylinder (ft.)

$$\frac{k}{t}(T-144) = 0.27\left(\frac{527-T}{d}\right)^{1/4}(527-T) + \sigma(527^4 - T^4)$$

$= 6.667\ ft$

$k = 4.8\ \frac{Btu}{hr\text{-}ft\,°F}$ (near 80K)

$$\frac{4.8}{.0208}(T-144) = .17(527-T)^{1/4}(527-T) + .1714\times10^{-8}(527^4 - T^4)$$

$$230.77(T-144) = .17(527-T)^{5/4} + .1714\times10^{-8}(527^4 - T^4)$$

Solution: $T = 146°R$

$$Q = .17(527-146)^{5/4} + .1714\times10^{-8}(527^4 - 146^4)$$

$$= 418\ \frac{Btu}{hr\text{-}ft^2}$$

$\therefore Q_{total} = 418 \frac{Btu}{hr-ft^2} \times \left(\frac{51876}{144}\right) ft^2$

$= 150,585 \frac{Btu}{hr}$

at 2 psig (16.7 psia) & 144 °R

$\beta = \frac{1}{V}\left(\frac{dV}{dT}\right)_p$

$= .00789 \quad 1/°R$

& $C_p = .27$ Btu/lbm-°R

$\therefore \dot{m} = \frac{(150585)(.00789)}{.27}$

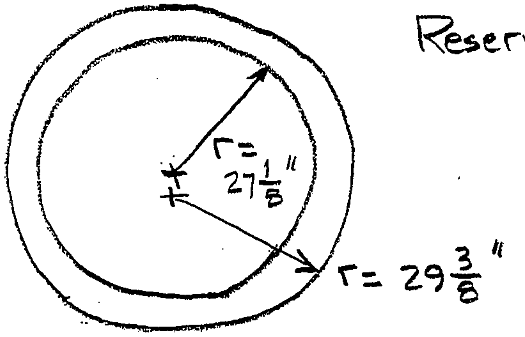
$= 4402 \frac{lbm}{hr} \quad \left(1.22 \frac{lbm}{sec}\right)$

//

Large gate valves at ends of pump are designed for $1\frac{3}{4}$ atm. differential pressure.

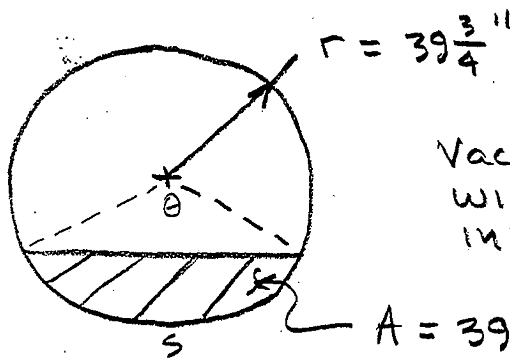
1.75 (14.7) = 25.73 psia (11 psig)

Case 2: Catastrophic rupture of LN_2 reservoir; LN_2 inventory collects at bottom of vacuum chamber; energy stored in 70°F vacuum chamber vaporizes liquid.



Reservoir (assume full)

$$A = \pi(29.375^2 - 27.125^2)$$
$$= 399.4 \text{ in}^2$$



Vacuum chamber with reservoir liquid inventory at bottom.

$A = 399.4 \text{ in}^2$

$$A = \frac{1}{2} r^2 (\theta - \sin\theta)$$

$$399.4 = \frac{1}{2}(39.75)^2(\theta - \sin\theta)$$

Solution: $\theta = 1.503$ rad.

Arclength s: $s = r\theta$
$$= 39.75(1.503)$$
$$= 59.74''$$

∴ Total area at the liquid/vacuum shell interface is approximately

$$(14\ ft)\left(\frac{12\ in.}{ft}\right)(59.74\ in.) = 10{,}036\ in^2$$
$$(69.69\ ft^2)$$

Due to the large temperature excess ($70°F - (-320°F)$), the liquid will form a vapor blanket between it & the vacuum chamber, resulting in film boiling.

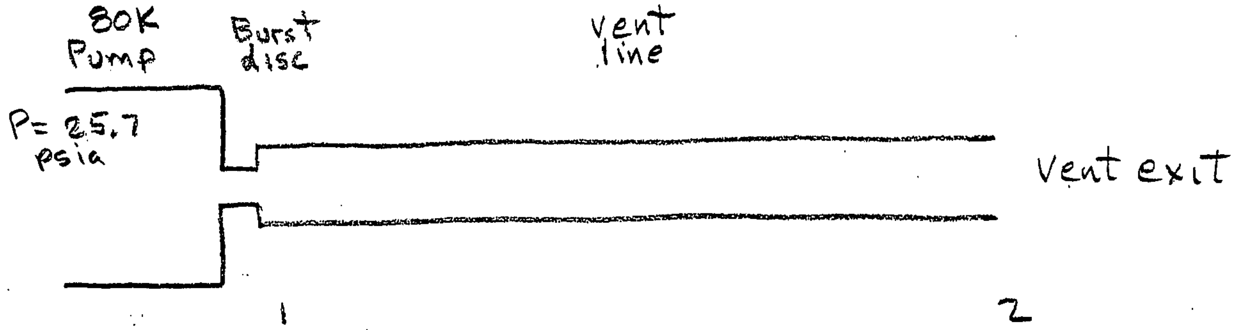
Referring to published boiling data for nitrogen, the heat flux at 390°F excess temperature is 8000 Btu/hr-ft²

$$\text{or } Q_{total} = 8000\,(69.69)$$
$$= 557{,}520\ Btu/hr$$

& vapor generation is:

$$\dot{m} = \frac{557{,}520\ Btu/hr}{85.46\ Btu/lbm}$$
$$= 6524\ lbm/hr.$$

Since mass flow rate is so large, pressure drop across vent line must be considered in sizing the required orifice area, and density changes must be considered.



Vent line length = 63.2 ft plus 4 - 90° miters (L_{equiv} = 63 ft)

Total L_{equiv} = 63.2 + 63 = 126.2 ft.

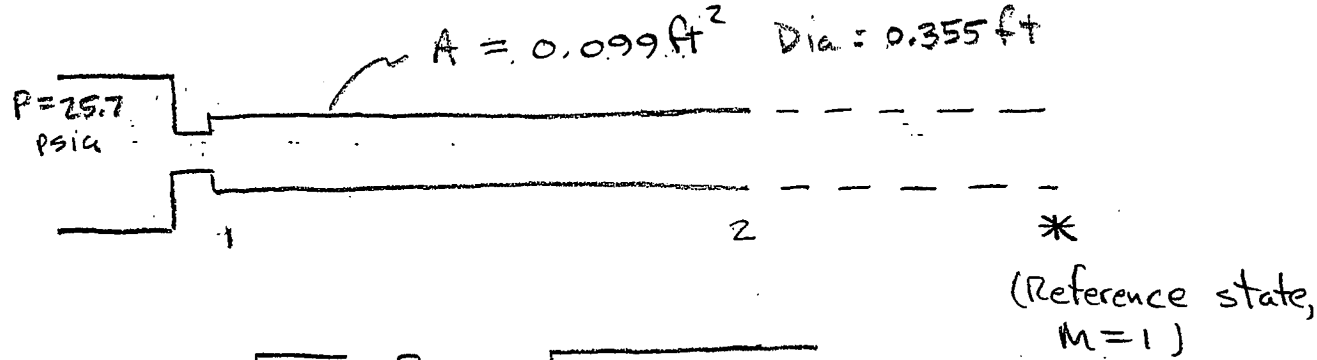
Since the pressure in the 80K pump is 25.7 psia, the flow in the vent will not choke & the pressure at the vent exit will be 14.7 psia.

Worst case assumption is that the vapor is that N_2 is at room temperature.

$\therefore$ P_3 = 25.7 psia

T_3 = 70 °F (530 °R)

= T_0 = constant (treat as adiabatic flow)



$$\frac{w}{a} = \sqrt{\frac{k}{R}}\,\frac{P}{\sqrt{T_o}}\,M\sqrt{1+\frac{k-1}{2}M^2}$$

$R = 55.13 \ \frac{ft-lb_f}{lb_m-°R}$ $\qquad P = 14.7(144) = 2117 \ \frac{lb_f}{ft^2}$

$$\frac{w}{A} = \frac{6524 \ lb_m/hr}{.099 \ ft^2} \times \frac{1}{3600} = 18.31 \ \frac{lb_m}{ft^2\text{-}sec}$$

Solve for M_2 :

$$18.31 = \sqrt{\frac{1.4(32.16)}{55.13}}\ \frac{2117}{\sqrt{460+70}}\ M\sqrt{1+.2M^2}$$

$$0.22 = M\sqrt{1+.2M^2}$$

	M	$M\sqrt{1+.2M^2}$
	.215	.216
	.217	.218
root →	.22	.221

$\therefore\ M_2 = .22 \quad \& \ (P/P^*)_{M_2} = 5.015$

From tables of compressible flow functions (pg 13, attached)

$$\left(4fL_{max}/D\right)_2 = 12.11$$

$$\text{Reynolds no} = \frac{\rho VD}{\mu} = \frac{wD}{\mu A}$$

$$= \frac{18.31(.355)}{1.17 \times 10^{-5}} \qquad \text{(Eval. at } 70\,°F)$$

$$= 555,600$$

$$4\bar{f} = .0172$$

$$\frac{4\bar{f}L}{D} = .0172\left(\frac{126.2}{.355}\right)$$

$$= 6.11$$

$$\frac{4\bar{f}L}{D} = \left(4\bar{f}\frac{L_{max}}{D}\right)_{M_1} - \left(4\bar{f}\frac{L_{max}}{D}\right)_{M_2}$$

$$\therefore \left(4\bar{f}\frac{L_{max}}{D}\right)_{M_1} = 6.11 + 12.11$$

$$= 18.22$$

From tables,

$$M_1 = .186$$

$$\text{\& } (P/P^*)_{M_1} = 5.96$$

$$\frac{P_2}{P_1} = \frac{(P/P^*)_{M2}}{(P/P^*)_{M1}}$$

$$\therefore P_1 = 14.7\left(\frac{5.96}{5.015}\right)$$

$$P_2 = 17.47 \text{ psia}$$

$\therefore$ Size burst disc for $25.7 - 17.47$

$= 8.23$ psid

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS
AMPAD

TABLE B.4

Frictional, Adiabatic, Constant-Area Flow (Fanno Line)

Perfect Gas, $k = 1.4$

M	T/T^*	p/p^*	p_0/p_0^*	V/V^* and ρ^*/ρ	F/F^*	$4fL_{max}/D$
0.00	1.2000	∞	∞	0.00000	∞	∞
.05	1.1994	21.903	11.5914	.05476	9.1584	280.02
.10	1.1976	10.9435	5.8218	.10943	4.6236	66.922
.15	1.1946	7.2866	3.9103	.16395	3.1317	27.932
.20	1.1905	5.4555	2.9635	.21822	2.4004	14.533
.25	1.1852	4.3546	2.4027	.27217	1.9732	8.4834
.30	1.1788	3.6190	2.0351	.32572	1.6979	5.2992
.35	1.1713	3.0922	1.7780	.37880	1.5094	3.4525
.40	1.1628	2.6958	1.5901	.43133	1.3749	2.3085
.45	1.1533	2.3865	1.4486	.48326	1.2763	1.5664
.50	1.1429	2.1381	1.3399	.53453	1.2027	1.06908
.55	1.1315	1.9341	1.2549	.58506	1.1472	.72805
.60	1.1194	1.7634	1.1882	.63481	1.10504	.49081
.65	1.10650	1.6183	1.1356	.68374	1.07314	.32460
.70	1.09290	1.4934	1.09436	.73179	1.04915	.20814
.75	1.07856	1.3848	1.06242	.77893	1.03137	.12728
.80	1.06383	1.2892	1.03823	.82514	1.01853	.07229
.85	1.04849	1.2047	1.02067	.87037	1.00966	.03632
.90	1.03270	1.12913	1.00887	.91459	1.00399	.014513
.95	1.01652	1.06129	1.00215	.95782	1.00093	.003280
1.00	1.00000	1.00000	1.00000	1.00000	1.00000	0
1.05	.98320	.94435	1.00203	1.04115	1.00082	.002712
1.10	.96618	.89359	1.00793	1.08124	1.00305	.009933
1.15	.94899	.84710	1.01746	1.1203	1.00646	.02053
1.20	.93168	.80436	1.03044	1.1583	1.01082	.03364
1.25	.91429	.76495	1.04676	1.1952	1.01594	.04858
1.30	.89686	.72848	1.06630	1.2311	1.02169	.06483
1.35	.87944	.69466	1.08904	1.2660	1.02794	.08199
1.40	.86207	.66320	1.1149	1.2999	1.03458	.09974
1.45	.84477	.63387	1.1440	1.3327	1.04153	.11782
1.50	.82759	.60648	1.1762	1.3646	1.04870	.13605
1.55	.81054	.58084	1.2116	1.3955	1.05604	.15427
1.60	.79365	.55679	1.2502	1.4254	1.06348	.17236
1.65	.77695	.53421	1.2922	1.4544	1.07098	.19022
1.70	.76046	.51297	1.3376	1.4825	1.07851	.20780
1.75	.74419	.49295	1.3865	1.5097	1.08603	.22504
1.80	.72816	.47407	1.4390	1.5360	1.09352	.24189
1.85	.71238	.45623	1.4952	1.5614	1.1009	.25832
1.90	.69686	.43936	1.5552	1.5861	1.1083	.27433
1.95	.68162	.42339	1.6193	1.6099	1.1155	.28989
2.00	.66667	.40825	1.6875	1.6330	1.1227	.30499
2.05	.65200	.39389	1.7600	1.6553	1.1297	.31965
2.10	.63762	.38024	1.8369	1.6769	1.1366	.33385
2.15	.62354	.36728	1.9185	1.6977	1.1434	.34760
2.20	.60976	.35494	2.0050	1.7179	1.1500	.36091

TABLE B.4. F

M	T/T^*
2.25	.59627
2.30	.58309
2.35	.57021
2.40	.55762
2.45	.54533
2.50	.53333
2.55	.52163
2.60	.51020
2.65	.49906
2.70	.48820
2.75	.47761
2.80	.46729
2.85	.45723
2.90	.4474
2.95	.4378
3.00	.4285
3.50	.3478
4.00	.2857
4.50	.2376
5.00	.2000
6.00	.1463
7.00	.1111
8.00	.0869
9.00	.0697
10.00	.0571
∞	0

Rev. 1

V049-1-094

Pg 13 of 15

Use sizing formula for subcritical flow from API 520:

for superimposed back pressure and for sizing a pilot-operated relief valve.

Note: Balanced-bellows relief valves that operate in the subcritical region should be sized using Equations 2–4. The back pressure correction factor for this application should be obtained from the valve manufacturer.

$$A = \frac{W}{735F_2K_d}\sqrt{\frac{ZT}{MP_1(P_1 - P_2)}} \quad (5)$$

$$A = \frac{V}{4645.2F_2K_d}\sqrt{\frac{ZTM}{P_1(P_1 - P_2)}} \quad (6)$$

$$A = \frac{V}{863.63F_2K_d}\sqrt{\frac{ZTG}{P_1(P_1 - P_2)}} \quad (7)$$

Where:

A = required effective discharge area of the valve, in square inches (see 1.2.2).

W = required flow through the valve, in pounds per hour.

F_2 = coefficient of subcritical flow (see Figure 29 for values)

$$= \sqrt{\left(\frac{k}{k-1}\right)(r)^{2/k}\left[\frac{1 - r^{(k-1)/k}}{1 - r}\right]}$$

k = ratio of the specific heats.

r = ratio of back pressure to upstream relieving pressure, P_2/P_1.

K_d = effective coefficient of discharge = 0.975 for use in Equations 5–7.

Z = compressibility factor for the deviation of the actual gas from a perfect gas, a factor evaluated at relieving inlet conditions.

T = relieving temperature of the inlet gas or vapor, in degrees Rankine (degrees Fahrenheit + 460).

M = molecular weight of the gas or vapor. Various handbooks carry tables of molecular weights of materials, but the composition of the flowing gas or vapor is seldom the same as that listed in the tables. This value should be obtained from the process data. Table 8 lists values for some common fluids.

P_1 = upstream relieving pressure, in pounds per square inch absolute. This is the set pressure plus the allowable overpressure (see 4.2) plus atmospheric pressure, in pounds per square inch absolute.

P_2 = back pressure, in pounds per square inch absolute.

V = required flow through the valve, in standard cubic feet per minute at 14.7 pounds per square inch absolute and 60°F.

G = specific gravity of gas referred to air = 1.00 for air at 14.7 pounds per square inch absolute and 60°F.

4.3.3 SIZING FOR SUBCRITICAL FLOW: GAS OR VAPOR OTHER THAN STEAM

4.3.3.1 General

When the ratio of back pressure to inlet pressure exceeds the critical pressure ratio P_{cf}/P_1, the flow through the pressure relief valve is subcritical (see 4.3.1). Equations 5–7 may be used to calculate the required effective discharge area for a conventional relief valve that has its spring setting adjusted to compensate

4.3.3.2 Example

In this example, the following relief requirements are given:

$$A = \frac{6524}{735(.811)(.975)} \times \sqrt{\frac{1.0\,(530)}{28.02(25.7)(25.7-17.47)}}$$

where:

$$r = \frac{17.47}{25.7} = 0.679$$

$$A = 3.357 \text{ in}^2$$

$$F_2 = \sqrt{\left(\frac{1.4}{.4}\right)(.679)^{1.429}} \times \sqrt{\frac{1-(.679)^{.286}}{1-.679}}$$

$$= .811$$

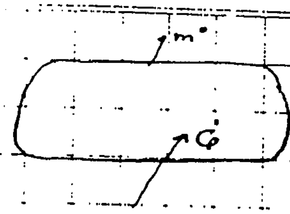
∴ Required diameter of relieving area is:

$$d = \sqrt{\frac{4A}{\pi}}$$

$$= \sqrt{\frac{4(3.357)}{\pi}}$$

$$d = 2.07 \text{ in.}$$

Attachment 1



mass Cons: $\dot m = \frac{dm}{dt}$

1st law: $\frac{d(mu)}{dt} = \frac{dQ}{dT} - h\dot m = \frac{dQ}{dt} + h\frac{dm}{dT}$

$$u\frac{dm}{dt} + m\frac{du}{dt} = \frac{dQ}{dt} + h\frac{dm}{dt}$$

$$m\frac{du}{dt} = \frac{dQ}{dt} + (h-u)\frac{dm}{dt}$$

$$h \triangleq u + pv$$

$$m\frac{du}{dt} = \frac{dQ}{dt} + pv\frac{dm}{dT}$$

$$\frac{dQ}{dt} = m\frac{du}{dt} - pv\frac{dm}{dT}$$

Const. volume (control volum): $m = \frac{V}{v}$ Const pressure process $h = u + pv$

$dh = du + p\,dv$

$$dm = -\frac{V\,dv}{v^2}$$

$$\frac{dQ}{dt} = m\frac{du}{dt} + \frac{Vp}{v}\frac{dv}{dT} = \frac{V}{v}\left(\frac{du}{dt} + p\frac{dv}{dt}\right) = \frac{V}{v}\frac{dh}{dT}$$

$$\dot m = \frac{dm}{dt} = -\frac{V}{v^2}\frac{dv}{dT}$$

$$\frac{\dot Q}{\dot m} = +\frac{v\,dh}{dv}$$

at const pressure $\left(\frac{T}{v}\frac{dv}{dT}\right) = \alpha$ & $\frac{dh}{dT} = c_p$

$$dh = c_p\,dT \quad \& \quad dv = \frac{\alpha}{T}v\,dT$$

$$\frac{dh}{dv} = \frac{c_pT}{\alpha v}$$

$$\frac{\dot Q}{\dot m} = \frac{c_pT}{\alpha} \Rightarrow \boxed{\dot m = \frac{\alpha\dot Q}{c_pT}}$$

But by definition,

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$$

$$\therefore \quad \frac{\dot{Q}}{\dot{m}} = \frac{c_p T}{\frac{T}{v}\left(\frac{\partial V}{\partial T}\right)}$$

$$= \frac{c_p}{\beta}$$

or $$\dot{m} = \frac{\dot{Q}\beta}{c_p}$$

PROCESS SYSTEMS INTERNATIONAL, INC   20 Walkup Drive, Westborough, MA 01581

CUSTOMER: LIGO

JOB NO:V59049

PRESSURE DROP ROUTE OR LINE ID:

PRESSURE:	100000.0 Pa	1.000 BAR
TEMPERATURE:	293.000 K	293.000 K
DENSITY :	1.150 KG/M^3	0.115E+01 KG/M^3
QUALITY :	1.000	

ITEMNAME	FLOWRATE KG/S	I.D. METER	K / DO	CV	LENGTH M	PRESSURE Pa	Z1 METER	Z2 METER	DP-F Pa	DP-Z Pa	DP-T Pa	DP-SUM Pa	DENSITY KG/M^3	VELOCITY M/S	RE NO
EQ PIPE LENGTH	0.800E-03	0.0900			1.00	99999.99	0.00	0.00	0.01	0.00	0.01	0.01	0.115E+01	0.109	0.642E+03
EXPANSION LOSS	0.800E-03	0.0900	1.5000			99999.982	0.00	0.00	0.01	0.00	0.01	0.02	0.115E+01		
								TOTAL	0.0179	0.0000		0.0179			

0.018 Pa = 0.0001 Torr ✓

$\frac{1}{2}\rho V^2 = \frac{1}{2} 1.1 \cdot 0.1^2 = 0.0055$ Pa.

No collapse problem due to pumpdown.

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1-096 PAGE 1 OF 12
REV.	DEO #	DATE	BY:	CHECK	TITLE: Regen. System Process Calculations	
Ø	130	4/19/96	D Moore	D.M.W		
					BY: D. Moore	DEPT.: 744

PROJECT: LIGO

PROJECT NO: V59049

PURPOSE: Determine process requirements for the 80K pump regen. heaters, and to estimate the warmup time (time to reach 150 deg. C) for the pump under wintertime conditions in Washington.

METHOD: Standard heat transfer manual calculations and on spreadsheet format.

ASSUMPTIONS: Used weather conditions for Kennewick, Washington: 15 deg. F dry bulb (Above this temperature 97.5% of the time.)

INPUTS: Max. regen flowrate = 100 gm/sec for long pump; 50 gm/sec for short pump. N2 temperature from the vaporizer = -5 deg. F (20 deg. F approach temp. specified by mfg.)

REFERENCES:

CALCULATIONS: See attached.

CONCLUSIONS: Long pump heater size: 25 kw adequate. Short pump heater size: 12 kw adequate. Estimated warmup times, including liquid vaporization: long pump = 16.75 hrs., short pump = 8.0 hrs.

80K Pump Regeneration
Process Calculations

Sizing of Regen Heaters:

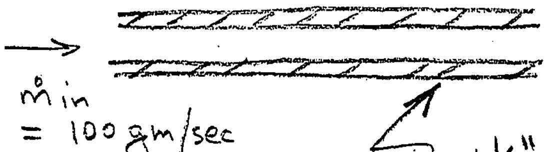
Heaters must be sized to deliver hot N_2 gas to the 80K pumps. The 80K pumps are to be heated to 302°F (150°C). Assuming a 20°F approach temperature, the gas temperature entering the cryopump should be about 325°F.

Wintertime Operation:

Using available design data, size the heater for 15°F dry bulb wintertime conditions (see Attachment 1). Assume a 10 m.p.h. wind blowing across the line supplying the regen. gas to the cryopump. ∴ Calculate the temperature exiting the heater in order to overcome heat losses from the supply line.

Heat Loss thru 60 ft. of regen pipe:

Long pump:



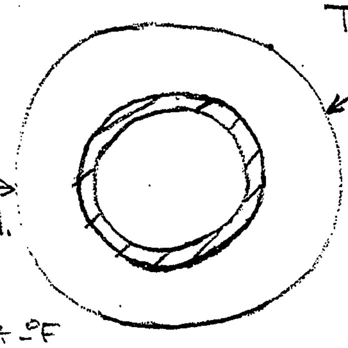
$\dot{m}_{in}$ = 100 gm/sec (.22 lbm/sec)

$1\frac{1}{2}$" insul. on 3" ϕ pipe

$T_{amb} = 15°F$

$T_{out} = 325°F$

$T_{in} = ?$



$T_o = ?$ $T_{amb} = 15°F$

$1\frac{1}{2}$" thk. insul.

$k = .04 \frac{Btu}{hr\text{-}ft\text{-}°F}$

Assume 10 mph wind

$$q_{in} = q_{out}$$

$$kS(T_i - T_o) = hA(T_o - T_{amb})$$

$$S = \frac{2\pi L}{\ln(r_o/r_i)}$$

$$= \frac{2\pi(1.0)}{\ln(6.5/3.5)} = 10.15 \text{ ft}$$

$$A = 2\pi r_o L$$

$$= 2\pi\left(\frac{3.25}{12}\right)(1.0)$$

$$= 1.70 \text{ ft}^2/\text{ft}$$

$$Re = \frac{D_o u_\infty}{\nu_f} = \frac{\rho_f D_o u_\infty}{\mu_f}$$

$$10 \frac{\text{mile}}{\text{hr}}\left(\frac{5280\ \text{ft}}{\text{mile}}\right) = 52800 \frac{\text{ft}}{\text{hr}}$$

$$Re = \frac{\left(\frac{6.5}{12}\right)(52800)(.084)}{.04} \qquad \mu_f = .04 \frac{\text{lbm}}{\text{hr-ft}}$$

$$= 60000$$

$$\frac{hD_o}{k_f} = 170 \quad \text{(see pg 7)}$$

$$h = \frac{170(.0135)}{(6.5/12)}$$

$$= 4.24 \quad \text{Btu/hr-ft}^2\text{-°F}$$

To account for radiation, say $h = 4.5 \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F}}$

$$\therefore \quad .04(10.15)(325 - T_o) = 4.5(1.70)(T_o - 15)$$

$$131.95 - .406T_o = 7.65T_o - 114.75$$

$$8.06T_o = 246.7$$

$$T_o = 30.6 \text{ °F}$$

$$\therefore \quad q = kS(T_i - T_o)$$

$$= .04(10.15)(325 - 30.6)$$

$$= 119.5 \frac{\text{Btu}}{\text{hr-ft}}$$

for 60 ft of pipe

$$q = 119.5(60) = 7172 \text{ Btu/hr}$$

∴ Calculate the temp drop of the N_2 inside the pipe

$$q = \dot{m} c_p \Delta T$$

$$7172 = .22(3600)(.25)\Delta T$$

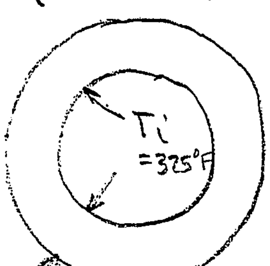
$$\Delta T = 36°F$$

N_2 temp in needs to be

$$\begin{array}{r} 325 \\ +\ 36 \\ \hline 361\ °F \end{array}$$ say 360°F

Short pump

1½" ϕ pipe
(1.9" o.d.)



1½" insul

50 gm/sec
(.11 lbm/sec)

$$S = \frac{2\pi(1.0)}{\ln(4.9/1.9)} = 6.63\ ft$$

$$A = 2\pi\left(\frac{4.9}{2(12)}\right)(1.0)$$

$$= 1.28\ ft^2/ft.$$

10 m.p.h. wind

$$R_e = \frac{\left(\frac{4.9}{12}\right)(52800)(.084)}{.04}$$

$$= 45300$$

$$\frac{h D_o}{k_f} = 150$$ (see pg 7)

$$h = \frac{150\,(.0135)}{(4.9/12)}$$

$$= 4.96 \ \text{Btu/hr-ft}^2\text{-°F}$$

say 5.5 Btu/hr-ft^2-°F

$$kS(T_i - T_o) = hA(T_o - T_{amb})$$

$$.04\,(6.63)(325 - T_o)$$
$$= 5.5\,(1.28)\,(T_o - 15)$$
$$86.19 - .265\,T_o = 7.04\,T_o - 105.6$$
$$191.8 = 7.305\,T_o$$
$$T_o = 26.3\text{°F}$$

$$q = kS(T_i - T_o)$$
$$= .04\,(6.63)(325 - 26.3)$$
$$= 79.21 \ \text{Btu/hr-ft}$$

for 60 ft of pipe

$$q = 60\,(79.21) = 4753 \ \text{Btu/hr}$$

∴ Temp drop of N_2:

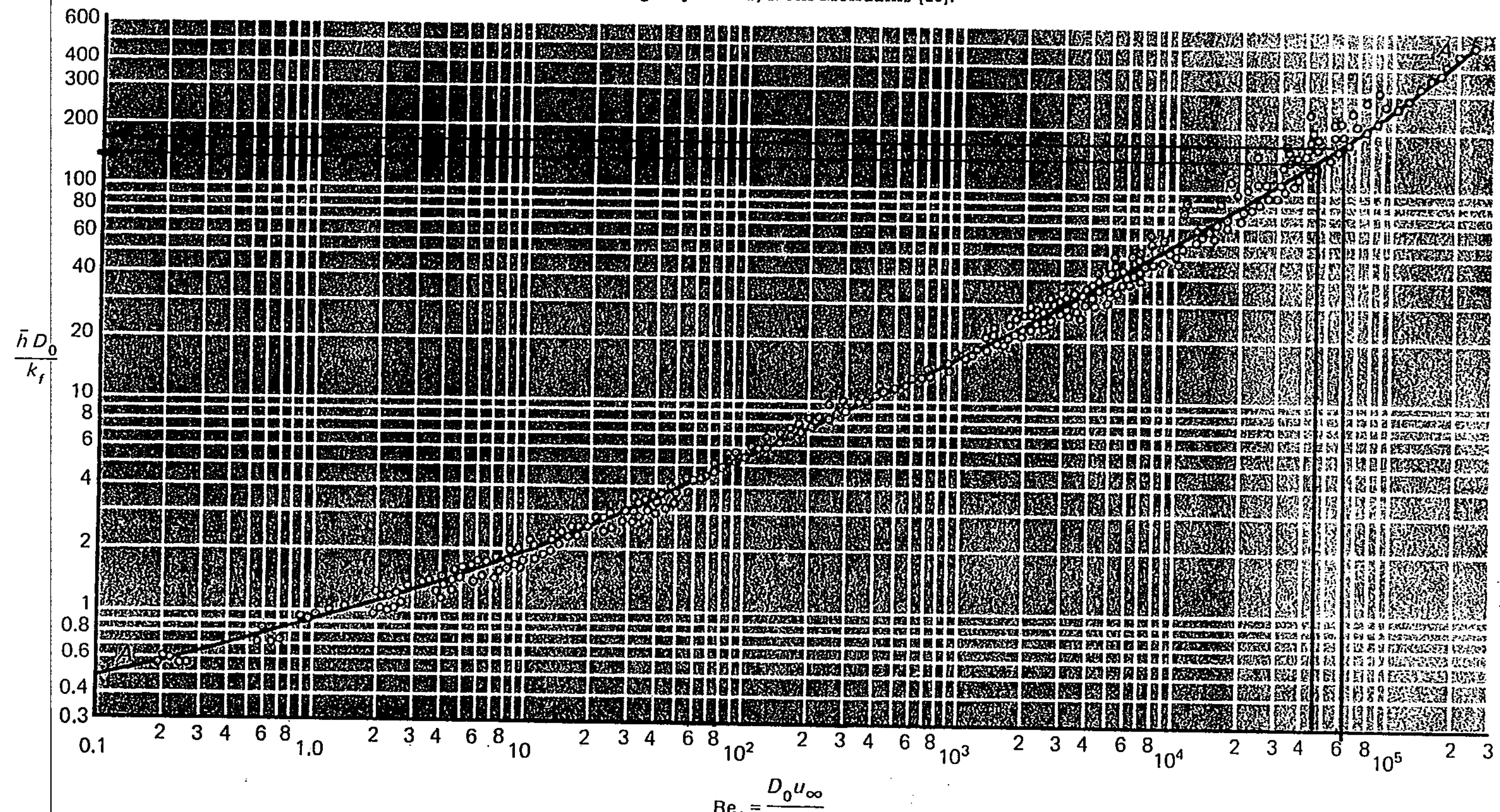
$$q = \dot{m} c_p \Delta T$$
$$4753 = .11\,(3600)(.25)\,\Delta T$$

$$\Delta T = 48\text{°F}$$

∴ T_{in} must be

$$\begin{array}{r} 325 \\ +\ 48 \\ \hline 373 \end{array}$$ (say 375°F)

Fig. 6-9 Data for heating and cooling of air flowing normal to single cylinders, from McAdams [10].



Pg 7 of 12
V049-1-096 REV0

Regen Heater Sizes:

Vaporizer design is based on 20°F approach temp. ∴ the N_2 gas out of the vaporizer will be 15°F - 20°F = -5°F (253 K)

Long pump:

100 gm/sec. flowrate at 253K raised to 455K (360 °F)

$$Q = \left(100 \frac{gm}{sec}\right)(472.8 - 262) \frac{j}{gm}$$

$$= 21080 \text{ watts}$$

(Heater size approx 25 kw)

100 gm/sec ⟶ 10572 SCFH (say 10600 SCFH)

Short pump:

50 gm/sec. flowrate at 253K raised to 464 K (375°F)

$$Q = 50 \frac{gm}{sec} (482.3 - 262) j/gm$$

$$= 11015 \text{ watts}$$ (Heater size approx 12 kw)

50 gm/sec ⟶ say 5300 SCFH

Time to vaporize LN_2:

Long pump: ~ 1700 lbm of LN_2 (772,700 gm)
Purge gas flow = 100 gm/sec.
@ 253K

$$(\dot{m}\Delta h)_{N_2\,gas} = \dot{m}\,h_{fg}$$

$$\dot{m}_{vaporized} = \frac{(\dot{m}\Delta h)_{N_2\,gas}}{h_{fg}}$$

$$= \frac{(100\text{ gm/sec})(262 - 79.6)\text{ j/gm}}{(78.4 + 118.1)\text{ j/gm}}$$

$$= 92.8\text{ gm/sec.}\ (.204\text{ lbm/sec})$$

∴ Time to vaporize is:

$$t = \frac{1702\text{ lbm}}{.204\text{ lbm/sec}}$$

$$= 8324\text{ sec}\ (2.3\text{ hr.})$$

Short pump: ~ 550 lbm of N_2
Purge gas flow = 50 gm/sec.

$$\dot{m}_{vaporized} = \frac{(50)(262 - 79.6)}{(78.4 + 118.1)}$$

$$= 46.4\text{ gm/sec}\ (.102\text{ lbm/sec})$$

∴ Time to vaporize is:

$$t = \frac{550}{.102} = 5392\text{ sec}\ (1.5\text{ hr.})$$

Long Pump Regen.
Warmup Time
Winter Conditions

N2 flow (gm/sec)	Cp of N2 (j/gm-K)	N2 in (K)	N2 out (K)	Cp alum. (j/gm-K)	Initial alum. temp (K)	Final alum. temp. (K)	Alum. mass (gm.)	Elapsed time (sec)
50	1.05	253	80	0.357	80	100	1341000	1054.2
50	1.05	253	100	0.481	100	120	1341000	2660.22
50	1.05	253	120	0.58	120	140	1341000	4888.02
50	1.05	253	140	0.654	140	160	1341000	7844.66
50	1.05	253	160	0.713	160	180	1341000	11761.2
50	1.05	253	180	0.76	180	200	1341000	17079.7
50	1.05	253	200	0.797	200	220	1341000	24761.9
100	1.05	436	220	0.826	220	240	1341000	25738.7
100	1.05	436	240	0.849	240	260	1341000	26845.1
100	1.05	436	260	0.869	260	280	1341000	28106.3
100	1.05	436	280	0.886	280	300	1341000	29557
100	1.05	436	300	0.902	300	320	1341000	31251.1
100	1.05	436	320	0.918	320	340	1341000	33272.5
100	1.05	436	340	0.934	340	360	1341000	35757.6
100	1.05	436	360	0.934	360	380	1341000	38896.7
100	1.05	436	380	0.934	380	400	1341000	43156.8
100	1.05	436	400	0.934	400	420	1341000	49783.8
100	1.05	436	420	0.934	420	423	1341000	52020.4

Time to vaporize LN2 = 2.3 hours
Total warmup time = 16.75 hours

Short Pump Regen.
Warmup Time
Winter Conditions

N2 flow (gm/sec)	Cp of N2 (j/gm-K)	N2 in (K)	N2 out (K)	Cp alum. (j/gm-K)	Initial alum. temp (K)	Final alum. temp. (K)	Alum. mass (gm.)	Elapsed time (sec)
50	1.05	253	80	0.357	80	100	398000	312.879
50	1.05	253	100	0.481	100	120	398000	789.537
50	1.05	253	120	0.58	120	140	398000	1450.73
50	1.05	253	140	0.654	140	160	398000	2328.25
50	1.05	253	160	0.713	160	180	398000	3490.66
50	1.05	253	180	0.76	180	200	398000	5069.16
50	1.05	253	200	0.797	200	220	398000	7349.16
50	1.05	436	220	0.826	220	240	398000	7928.97
50	1.05	436	240	0.849	240	260	398000	8585.73
50	1.05	436	260	0.869	260	280	398000	9334.34
50	1.05	436	280	0.886	280	300	398000	10195.5
50	1.05	436	300	0.902	300	320	398000	11201.1
50	1.05	436	320	0.918	320	340	398000	12400.9
50	1.05	436	340	0.934	340	360	398000	13876.1
50	1.05	436	360	0.934	360	380	398000	15739.4
50	1.05	436	380	0.934	380	400	398000	18268.2
50	1.05	436	400	0.934	400	420	398000	22201.8
50	1.05	436	420	0.934	420	423	398000	23529.5

Time to vaporize LN2 = 1.5 hours
Total warmup time = 8.036 hours

Attachment 1.

Table C-1 (Cont.)

STATE AND STATION	WINTER Latitude	WINTER DB 97½%	SUMMER DB 2½%	SUMMER WB 2½%	SUMMER Outdoor Daily Range
Lubbock AP	33	15	97	72	26
Lufkin AP	31	28	96	80	20
McAllen	26	38	100	79	21
Midland AP	32	23	98	73	26
Mineral Wells AP	32	22	100	77	22
Palestine CO	31	25	97	79	20
Pampa	35	11	98	72	26
Pecos	31	19	100	71	27
Plainview	34	14	98	72	26
Port Arthur AP	30	33	92	80	19
San Angelo, Goodfellow AFB	31	25	99	75	24
San Antonio AP	29	30	97	77	19
Sherman-Perrin AFB	33	23	99	78	22
Snyder	32	19	100	74	26
Temple	31	27	99	78	22
Tyler AP	32	24	97	79	21
Vernon	34	18	101	76	24
Victoria AP	28	32	96	79	18
Waco AP	31	26	99	78	22
Wichita Falls AP	34	19	100	76	24
UTAH					
Cedar City AP	37	6	91	64	32
Logan	41	7	91	65	33
Moab	38	16	98	65	30
Ogden CO	41	11	92	65	33
Price	39	7	91	64	33
Provo	40	6	93	66	32
Richfield	38	3	92	65	34
St. George CO	37	26	102	70	33
Salt Lake City AP	40	9	94	66	32
Vernal AP	40	− 6	88	63	32
VERMONT					
Barre	44	−13	84	72	23
Burlington AP	44	− 7	85	73	23
Rutland	43	− 8	85	73	23
VIRGINIA					
Charlottsville	38	15	90	77	23
Danville AP	36	17	92	77	21
Fredericksburg	38	14	92	78	21
Harrisonburg	38	9	90	77	23
Lynchburg AP	37	19	92	76	21
Norfolk AP	36	23	91	78	18
Petersburg	37	18	94	79	20
Richmond AP	37	18	93	78	21
Roanoke AP	37	18	91	75	23
Staunton	38	12	90	77	23
Winchester	39	10	92	76	21
WASHINGTON					
Aberdeen	47	27	80	61	16
Bellingham AP	48	18	74	65	19
Bremerton	47	29	81	66	20
Ellensburg AP	47	6	89	65	34

STATE AND STATION	WINTER Latitude	WINTER DB 97½%	SUMMER DB 2½%	SUMMER WB 2½%	SUMMER Outdoor Daily Range
Everett-Paine AFB	47	24	78	65	20
Kennewick	46	$\boxed{15}$	96	68	30
Longview	46	24	86	66	30
Moses Lake, Larson AFB	47	− 1	93	66	32
Olympia AP	47	25	83	65	32
Port Angeles	48	29	73	58	18
Seattle-Boeing Fld.	47	27	80	65	24
Seattle CO	47	32	79	65	19
Seattle-Tacoma AP	47	24	81	64	22
Spokane AP	47	4	90	64	28
Tacoma-McChord AFB	47	24	81	66	22
Walla Walla AP	46	16	96	68	27
Wenatchee	47	9	92	66	32
Yakima AP	46	10	92	67	36
WEST VIRGINIA					
Beckley	37	6	88	73	22
Bluefield AP	37	10	86	73	22
Charleston AP	38	14	90	75	20
Clarksburg	39	7	90	75	21
Elkins AP	38	5	84	73	22
Huntington CO	38	14	93	76	22
Martinsburg AP	39	10	94	77	21
Morgantown AP	39	7	88	74	22
Parkersburg CO	39	12	91	76	21
Wheeling	40	9	89	75	21
WISCONSIN					
Appleton	44	− 6	87	74	23
Ashland	46	−17	83	71	23
Beloit	42	− 3	90	76	24
Eau Claire AP	44	−11	88	74	23
Fond du Lac	43	− 7	87	74	23
Green Bay AP	44	− 7	85	73	23
La Crosse AP	43	− 8	88	76	22
Madison AP	43	− 5	88	75	22
Manitowoc	44	− 1	86	74	21
Marinette	45	− 4	86	72	20
Milwaukee AP	43	− 2	87	75	21
Racine	42	0	88	75	21
Sheboygan	43	0	87	74	20
Stevens Point	44	−12	87	73	23
Waukesha	43	− 2	89	75	22
Wausau AP	44	−14	86	72	23
WYOMING					
Casper AP	42	− 5	90	62	31
Cheyenne AP	41	− 2	86	62	30
Cody AP	44	− 9	87	60	32
Evanston	41	− 8	82	57	32
Lander AP	42	−12	90	62	32
Laramie AP	41	− 2	80	59	28
Newcastle	43	− 5	89	67	30
Rawlins	41	−11	84	61	40
Rock Springs AP	41	− 1	84	57	32
Sheridan AP	44	− 7	92	65	32
Torrington	42	− 7	92	67	30

EXPLANATION OF DESIGN CONDITIONS:

WINTER – 97½% indicates that the temperature will be at or above the design temperature shown 97½% of the time.

SUMMER – 2½% indicates that the temperature will exceed the design temperature shown only 2½% of the time.

OUTDOOR DAILY RANGE – The outdoor daily range of DB temperatures is the difference between the average maximum and average minimum temperatures during the warmest month at each location. Refer to page 39 when outdoor daily range is other than 20°.

PROCESS SYSTEMS INTERNATIONAL, INC. WESTBOROUGH, MA					ENGINEERING CALCULATIONS	NO: V049-1- 116 PAGE 1 OF 21
REV.	DEO #	DATE	BY:	CHECK	TITLE: 80K Pump Liquid Supply Valve Sizing	
0	5311	10/17/96	DM	D.Mcw		
					BY: D. Moore	DEPT.: 744

PROJECT: LIGO Vacuum Equipment

PROJECT NO: V59049

PURPOSE: Calculate required Cv for the liquid supply valve for the range of operating conditions that the pump will experience.

METHOD: Standard ISA formulas used in sizing control valves for two phase flow. Calculations have been programmed.

ASSUMPTIONS: a) Liquid nitrogen dewar full. b) Liquid nitrogen dewar 20% full c) 80K pump clean d) 80K pump frosted

INPUTS:

REFERENCES: ISA SP39.1 formulas for control valve sizing (excerpt of paper attached).

CALCULATIONS: (SEE ATTACHED)

CONCLUSIONS: Use valve plug with maximum Cv of 0.05. Minimum requirement is 0.0056.

NOTES:

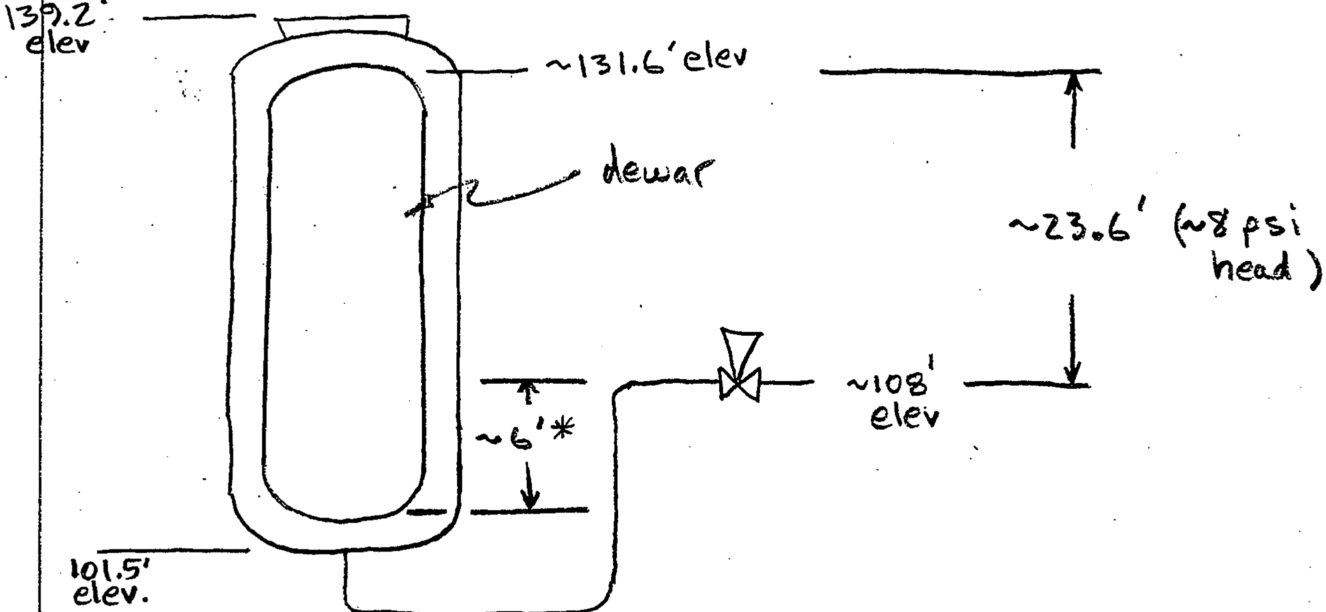
REVISION HISTORY

Rev. 0	Original Issue -Oct. 17, 1996

LN_2 Dewar Short Pump

Set reguator at 5 psig (top of tank)
Pressure at control valve is 5 psig + liquid head

Tank full: 5 + 8 = 13 psig at valve
Tank "empty": 5 psig at valve
(≈20% full)

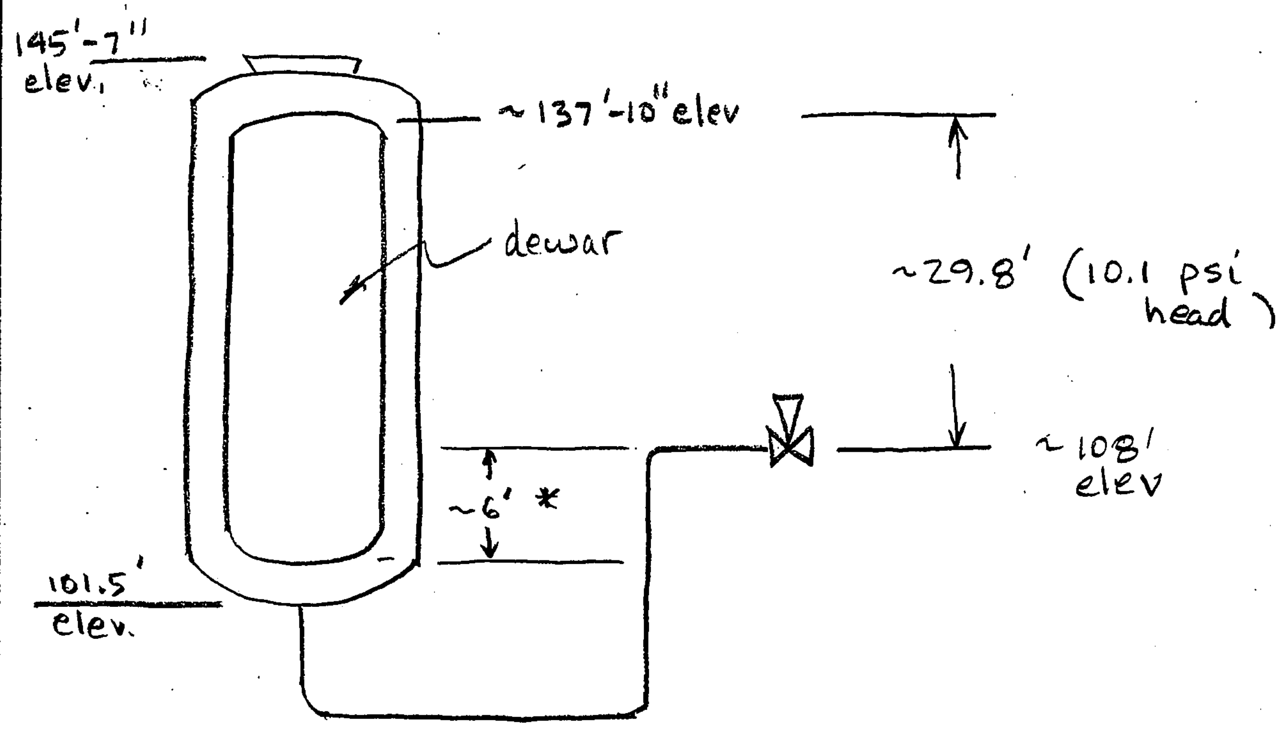


* approx. 20% of height of dewar

LN_2 Dewar
Long Pump

Set regulator at 5 psig (top of tank)
Pressure at control valve is 5 psig + liquid head

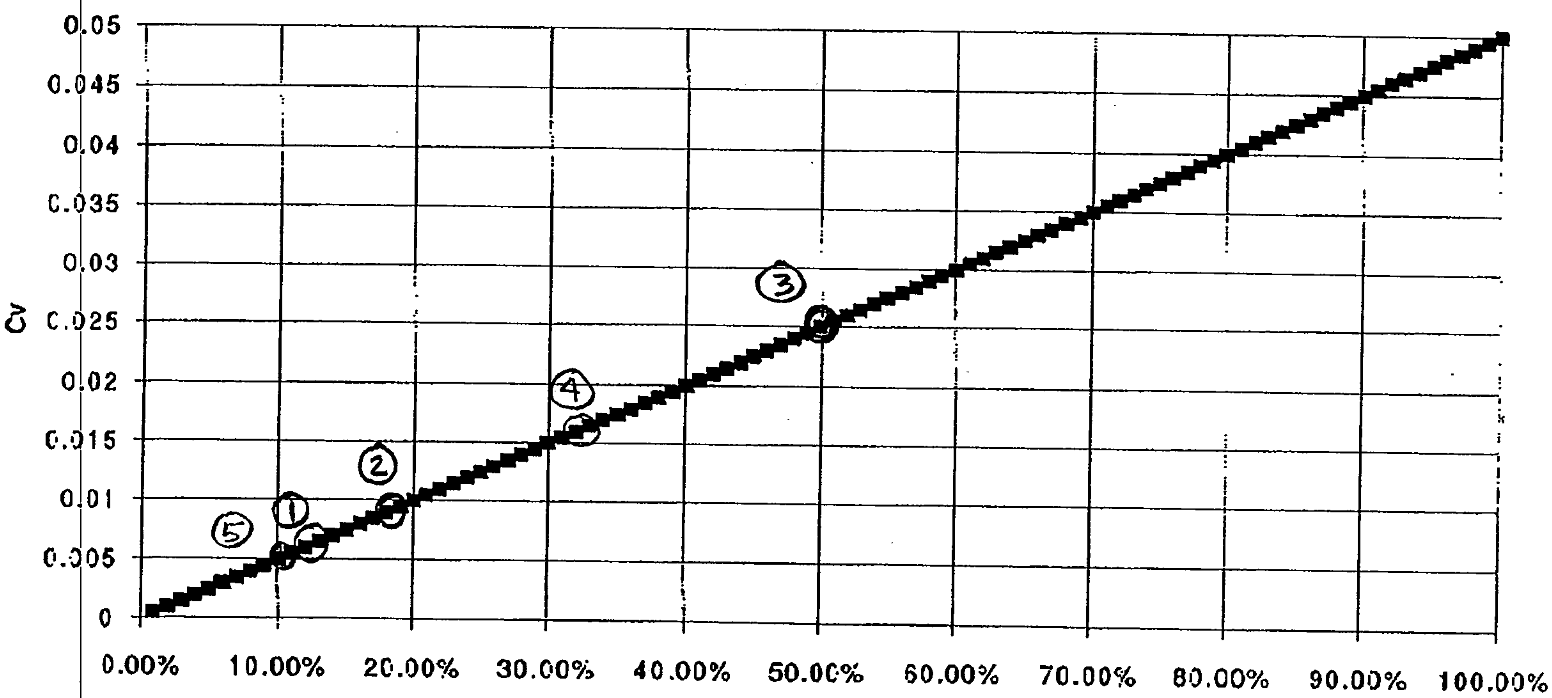
Tank full : 5 + 10 = 15 psig at valve
Tank "empty" : 5 psig at valve
(~16.5 % full)



* approx 16.5% of height of dewar

Short Pump

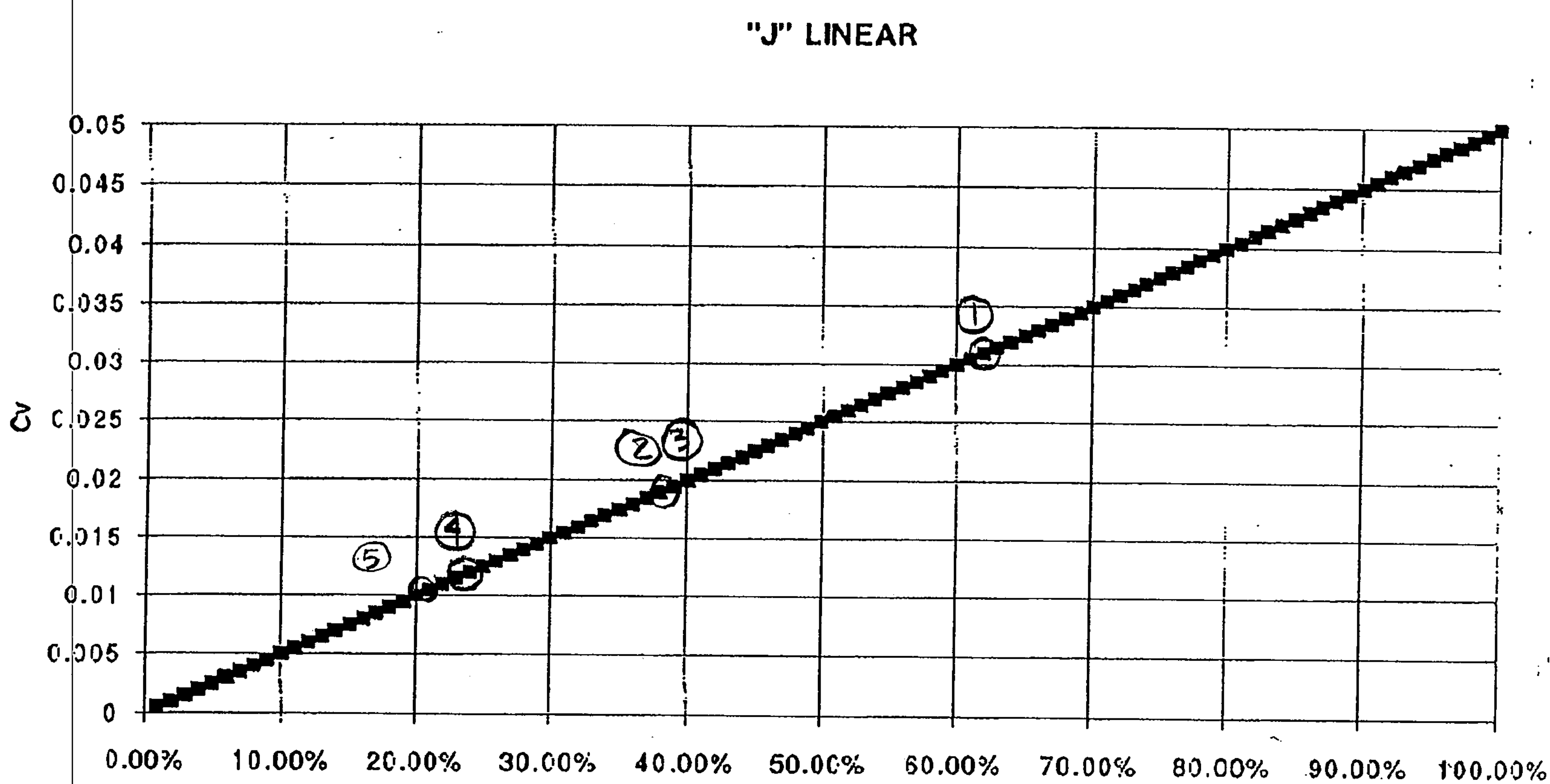
"J" LINEAR



1. Clean, 13 psid ΔP (Tank full)
2. Clean, 5 psid ΔP (Tank 20% full)
3. Frosted, 5 psid ΔP
4. Frosted, 13 psid ΔP
5. Clean, 13 psid ΔP, subcooled case

V049-1-116, Rev 0
Pg 5 of 21

Long Pump



1 Frosted, 5 psid ΔP (Tank 16.5% full)

2 Clean, 5 psid ΔP

3 Frosted, 15 psid ΔP (Tank full)

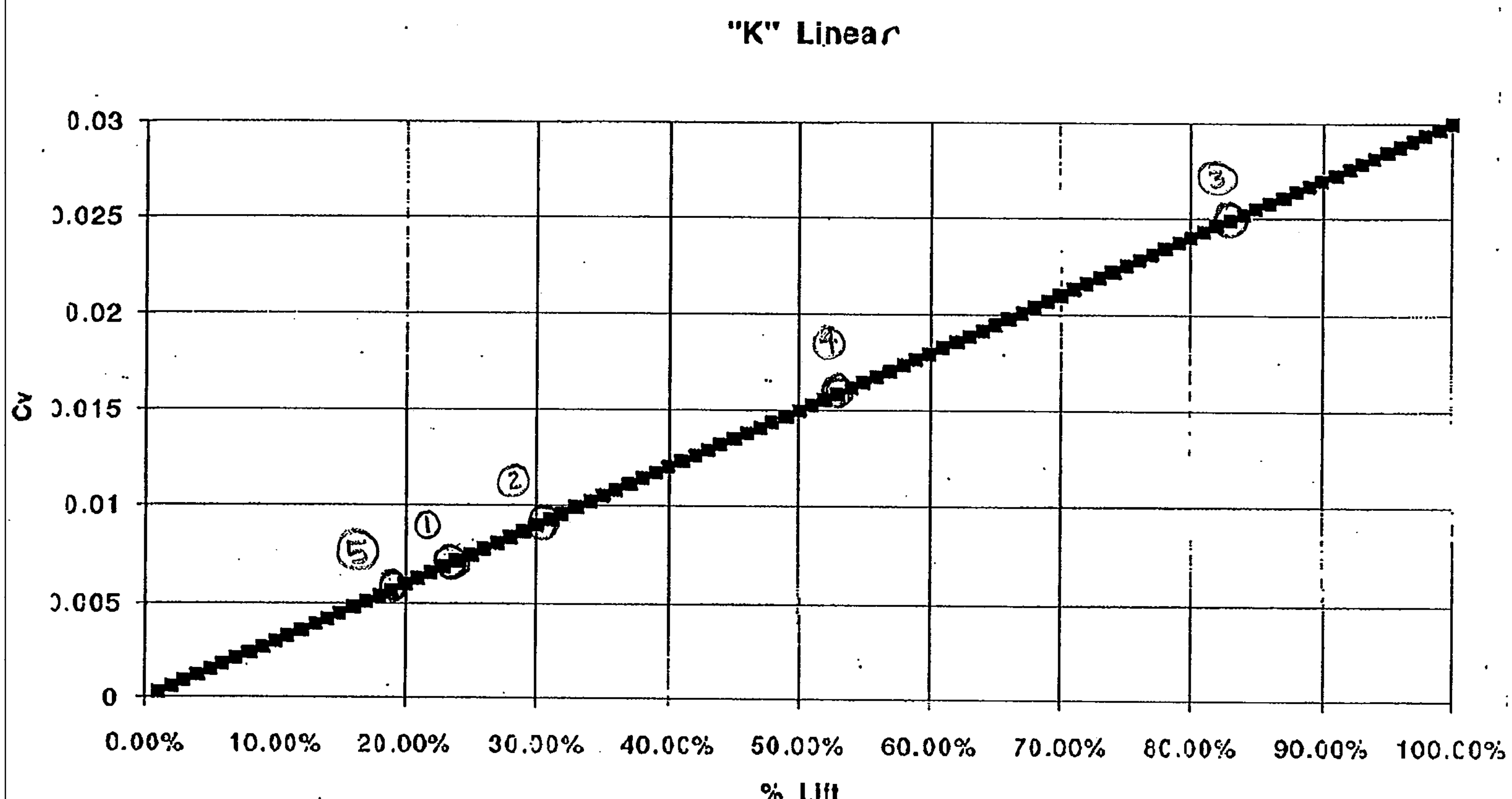
4 Clean, 15 psid ΔP

5 Clean, 15 psid ΔP, subcooled liquid

V049-1-116, Rev 0
Pg 6 of 21

Short Pump

Smaller Cv



1. Pump clean, 13 psid ΔP (Dewar full).
2. Pump clean, 5 psid ΔP (Dewar 20% full)
3. Pump frosted, 5 psid ΔP
4. Pump frosted, 13 psid ΔP
5. Pump clean, 13 psid ΔP, liquid subcooled

Viewing: VALVSIZ.OUT Press ESC to exit (F)ilter OFF

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR FROSTED LONG PUMP, 5 PSID AVAILABLE

```
LIQUID FLOW RATE THRU VALVE =   31.410 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =      .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =    5.000 PSID
CF(CRITICAL FLOW FACTOR) =    .90
PRESSURE UPSTREAM OF VALVE =   19.700 PSIA
UPSTREAM FLUID QUALITY =   .000
FLOW IS SUBCRITICAL ACROSS VALVE
DELTA P USED IN SIZING FORMULA =  5.000 PSID
REQUIRED VALVE CV =     .031
```

Commands PGUP PGDN HOME END 1..9 scroll ↓ (H)ex (N)ormal (S)earch

V049-1-116, Rev 0
Pg 7 of 21

```
Viewing: VALVSIZ.OUT          Press ESC to exit                 (F)ilter OFF

LIGO LIQUID SUPPLY VALVE

 REQUIRED CV FOR CLEAN LONG PUMP, 5 PSID AVAILABLE

         LIQUID FLOW RATE THRU VALVE =    19.240 LBM/HR
         LIQUID DENSITY =    49.690 LBM/FT**3
         VAPOR DENSITY =      .383 LBM/FT**3
         VAPOR PRESSURE =    14.700 PSIA
         CRITICAL PRESSURE =  492.000 PSIA
         VALVE DELTA P =     5.000 PSID
         CF(CRITICAL FLOW FACTOR) =     .90
         PRESSURE UPSTREAM OF VALVE =    19.700 PSIA
         UPSTREAM FLUID QUALITY =    .000
         FLOW IS SUBCRITICAL ACROSS VALVE
         DELTA P USED IN SIZING FORMULA =  5.000 PSID
         REQUIRED VALVE CV =      .019

Commands PGUP  PGDN  HOME  END 1..9 scroll  ↓ (H)ex (N)ormal (S)earch
```

V049-1-116, Rev 0
Pg 8 of 21

Viewing: VALVSIZ.OUT　　Press ESC to exit　　(F)ilter OFF

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR FROSTED LONG PUMP,15 PSID AVAILABLE

```
LIQUID FLOW RATE THRU VALVE =    31.410 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =      .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =   15.000 PSID
CF(CRITICAL FLOW FACTOR) =     .90
PRESSURE UPSTREAM OF VALVE =   29.700 PSIA
UPSTREAM FLUID QUALITY =    .000
CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
REQUIRED VALVE CV =      .019
```

Commands PGUP　PGDN　HOME　END 1..9 scroll　↓　(H)ex　(N)ormal　(S)earch

```
Viewing: VALVSIZ.OUT              Press ESC to exit                  (F)ilter OFF
```

```
LIGO LIQUID SUPPLY VALVE

 REQUIRED CV FOR CLEAN LONG PUMP, 15 PSID AVAILABLE

          LIQUID FLOW RATE THRU VALVE =    19.240 LBM/HR
          LIQUID DENSITY =    49.690 LBM/FT**3
          VAPOR DENSITY =      .383 LBM/FT**3
          VAPOR PRESSURE =    14.700 PSIA
          CRITICAL PRESSURE =   492.000 PSIA
          VALVE DELTA P =    15.000 PSID
          CF(CRITICAL FLOW FACTOR) =     .90
          PRESSURE UPSTREAM OF VALVE =    29.700 PSIA
          UPSTREAM FLUID QUALITY =    .000
          CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
          REQUIRED VALVE CV =      .012
```

```
Commands PGUP  PGDN  HOME  END 1..9 scroll  ↓ (H)ex (N)ormal (S)earch
```

```
Viewing: VALVSIZ.OUT            Press ESC to exit                (F)ilter OFF

IGO LIQUID SUPPLY VALVE

 REQUIRED CV FOR CLEAN SHORT PUMP,13 PSID AVAILABLE

          LIQUID FLOW RATE THRU VALVE =    9.000 LBM/HR
          LIQUID DENSITY =   49.690 LBM/FT**3
          VAPOR DENSITY =     .383 LBM/FT**3
          VAPOR PRESSURE =   14.700 PSIA
          CRITICAL PRESSURE =  492.000 PSIA
          VALVE DELTA P =   13.000 PSID
          CF(CRITICAL FLOW FACTOR) =     .90
          PRESSURE UPSTREAM OF VALVE =   27.700 PSIA
          UPSTREAM FLUID QUALITY =    .000
          CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
          REQUIRED VALVE CV =     .006

Commands PGUP  PGDN  HOME  END 1..9 scroll  ↓ (H)ex (N)ormal (S)earch
```

V049-1-116, Rev 0
Pg 11 of 21

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR CLEAN SHORT PUMP,5 PSID AVAILABLE

```
LIQUID FLOW RATE THRU VALVE =    9.000 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =     .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =    5.000 PSID
CF(CRITICAL FLOW FACTOR) =     .90
PRESSURE UPSTREAM OF VALVE =    19.700 PSIA
UPSTREAM FLUID QUALITY =    .000
FLOW IS SUBCRITICAL ACROSS VALVE
DELTA P USED IN SIZING FORMULA =  5.000 PSID
REQUIRED VALVE CV =     .009
```

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR FROSTED SHORT PUMP,5 PSID AVAILABLE

```
LIQUID FLOW RATE THRU VALVE =    24.690 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =     .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =    5.000 PSID
CF(CRITICAL FLOW FACTOR) =    .90
PRESSURE UPSTREAM OF VALVE =   19.700 PSIA
UPSTREAM FLUID QUALITY =    .000
FLOW IS SUBCRITICAL ACROSS VALVE
DELTA P USED IN SIZING FORMULA =  5.000 PSID
REQUIRED VALVE CV =     .025
```

Viewing: VALVSIZ.OUT Press ESC to exit (F)ilter OFF

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR FROSTED SHORT PUMP,13 PSID AVAILABLE

```
LIQUID FLOW RATE THRU VALVE =    24.690 LBM/HR
LIQUID DENSITY =    49.690 LBM/FT**3
VAPOR DENSITY =      .383 LBM/FT**3
VAPOR PRESSURE =    14.700 PSIA
CRITICAL PRESSURE =   492.000 PSIA
VALVE DELTA P =    13.000 PSID
CF(CRITICAL FLOW FACTOR) =      .90
PRESSURE UPSTREAM OF VALVE =    27.700 PSIA
UPSTREAM FLUID QUALITY =    .000
CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
REQUIRED VALVE CV =      .016
```

Commands PGUP PGDN HOME END 1..9 scroll ↓ (H)ex (N)ormal (S)earch

V049-1-116, Rev 0
Pg 19 of 21

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR CLEAN SHORT PUMP,13 PSID AVAILABLE,SUBCOOLED CASE

```
LIQUID SERVICE
LIQUID FLOW RATE THRU VALVE =     9.000 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =      .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =   13.000 PSID
PRESSURE UPSTREAM OF VALVE =   27.700 PSIA
UPSTREAM FLUID QUALITY =   .000
REQUIRED VALVE CV =     .0056
```

LIGO LIQUID SUPPLY VALVE

REQUIRED CV FOR CLEAN LONG PUMP,15 PSID AVAILABLE,SUBCOOLED CASE

```
LIQUID SERVICE
LIQUID FLOW RATE THRU VALVE =    19.240 LBM/HR
LIQUID DENSITY =   49.690 LBM/FT**3
VAPOR DENSITY =      .383 LBM/FT**3
VAPOR PRESSURE =   14.700 PSIA
CRITICAL PRESSURE =  492.000 PSIA
VALVE DELTA P =   15.000 PSID
PRESSURE UPSTREAM OF VALVE =    29.700 PSIA
UPSTREAM FLUID QUALITY =    .000
REQUIRED VALVE CV =     .0111
```

V049-1-116, Rev 0
Pg 15 of 21

```
C---------DATE: OCT. 1996
C-------- PROGRAMMER: DAVID MOORE
C
                         PROGRAM    VALVSIZ2
C                          VERSION 2.0
C
C--- THESE COMPUTATIONS ARE FOR 2 PHASE FLOW AND LIQUID FLOW THRU VALVES
C--- FORMULAS ARE COMPATIBLE WITH ISA SP39.1 AND ARE FROM MASONNEILAN
C--- PAPER ON CONTROL VALVE SIZING.
C
C--- NOTE: NO LOGIC IS PRESENTLY IN THIS CODE TO ACCOUNT FOR
C---       NON-CONDENSABLE GAS.
C
      REAL MDOTL
      CHARACTER TITLE1*80,TITLE2*80
      OPEN(UNIT=10,FILE='VALVSIZ.DAT',ACCESS='SEQUENTIAL',STATUS='OLD',
     +     FORM='FORMATTED')
      OPEN(UNIT=11,FILE='VALVSIZ.OUT',ACCESS='SEQUENTIAL',STATUS='OLD',
     +     FORM='FORMATTED')
$DEBUG
C
C-----READ DATA----------
      READ(10,*) TITLE1
      READ(10,*) TITLE2
      WRITE(11,*) TITLE1
      WRITE(11,*) TITLE2
C--- READ VALUE OF FLAGS. IF FLAG1 IS GREATER THAN 0.0, CALCULATE THE
C--- FLOWRATE WHEN GIVEN THE CV AND VALVE DP. OTHERWISE CALCULATE
C--- THE REQ'D CV. FLAG2 GREATER THAN 0.0 IS FOR LIQUID SERVICE.
C
      READ(10,*) FLAG1,FLAG2
C
C--- READ CV, LIQ. DENS(LB/FT**3),LIQ. VAPOR PRESS AT FLOWING TEMP(PSIA),
C---THERMODYNAMIC CRITICAL PRESS.(PSIA), DELTA P ACROSS VALVE(PSIA)
      IF(FLAG1.GT.0.0.AND.FLAG2.EQ.0.0)THEN
C-----FLASHING FLOW
       READ(10,*) CV,RHOL,RHOV,VAPRES,CRPRES,DPVALV,CF,P1,X
       WRITE(11,100)CV
       WRITE(11,101)RHOL
       WRITE(11,111)RHOV
       WRITE(11,102)VAPRES
       WRITE(11,103)CRPRES
       WRITE(11,104)DPVALV
       WRITE(11,105)CF
       WRITE(11,106)P1
       WRITE(11,110)X
       DPMAX=CF**2*P1/2.0
       DPS=P1-(0.96-0.28*SQRT(VAPRES/CRPRES))*VAPRES
C
       CF2DP=CF**2*DPS
       DPWL=DPVALV*(RHOL/62.4/(RHOL/62.365))
        IF(CF2DP.LT.DPWL)THEN
         WRITE(11,107)
C--- CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
         MDOTL=CV*500*CF*SQRT(DPS*(RHOL/62.365))
         WRITE(11,109)MDOTL
        ELSE
         WRITE(11,112)
C--- FLOW IS TWO-PHASE LIQUID & VAPOR, NO NON-CONDENSABLES & NO CHOKING
```

V049-1-116, Rev 0
Pg 7 of 21

```
         W1=1.0/(X*(1/RHOV+1/RHOL)+1/RHOL)
          IF(DPVALV.GE.DPMAX)THEN
C--- MAX DELTA P FOR SIZING SUBSTITUTED FOR DPVALV
           DPVALV=DPMAX
           WRITE(11,108)DPVALV
          ELSE
           WRITE(11,108)DPVALV
          END IF
         MDOTL=CV*63.3*SQRT(DPVALV*W1)
         WRITE(11,109)MDOTL
       END IF
        ELSE IF(FLAG1.GT.0.0.AND.FLAG2.GT.0.0)THEN
         READ(10,*) CV,RHOL,RHOV,VAPRES,CRPRES,DPVALV,CF,P1,X
C--- LIQUID OR SUBCOOLED SERVICE
         WRITE(11,114)
         MDOTL=CV*500*SQRT(RHOL/62.4*DPVALV)
         WRITE(11,109)MDOTL
        ELSE IF(FLAG1.EQ.0.0.AND.FLAG2.EQ.0.0)THEN
         READ(10,*) CV,RHOL,RHOV,VAPRES,CRPRES,DPVALV,CF,P1,X
C---- FLASHING FLOW
C---  CODE HERE FOR CALCULATION OF CV WHEN GIVEN FLOW RATE
       READ(10,*) MDOTL,RHOL,RHOV,VAPRES,CRPRES,DPVALV,CF,P1,X
       WRITE(11,109)MDOTL
       WRITE(11,101)RHOL
       WRITE(11,111)RHOV
       WRITE(11,102)VAPRES
       WRITE(11,103)CRPRES
       WRITE(11,104)DPVALV
       WRITE(11,105)CF
       WRITE(11,106)P1
       WRITE(11,110)X
       DPMAX=CF**2*P1/2.0
       DPS=P1-(0.96-0.28*SQRT(VAPRES/CRPRES))*VAPRES
C
       CF2DP=CF**2*DPS
       DPWL=DPVALV*(RHOL/62.4/(RHOL/62.365))
        IF(CF2DP.LT.DPWL)THEN
         WRITE(11,107)
C--- CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS
         CV=MDOTL/(500*CF*SQRT(DPS*(RHOL/62.365)))
         WRITE(11,113)CV
        ELSE
         WRITE(11,112)
C--- FLOW IS TWO-PHASE LIQUID & VAPOR, NO NON-CONDENSABLES & NO CHOKING
         W1=1.0/(X*(1/RHOV+1/RHOL)+1/RHOL)
          IF(DPVALV.GE.DPMAX)THEN
C--- MAX DELTA P FOR SIZING SUBSTITUTED FOR DPVALV
           DPVALV=DPMAX
           WRITE(11,108)DPVALV
          ELSE
           WRITE(11,108)DPVALV
          END IF
         CV=MDOTL/(63.3*SQRT(DPVALV*W1))
         WRITE(11,113)CV
       END IF
        ELSE IF(FLAG1.EQ.0.0.AND.FLAG2.GT.0.0)THEN
       READ(10,*) MDOTL,RHOL,RHOV,VAPRES,CRPRES,DPVALV,CF,P1,X
       WRITE(11,114)
       WRITE(11,109)MDOTL
       WRITE(11,101)RHOL
```

V049-1-116, Rev 0
Pg 18 of 21

```
      WRITE(11,111)RHOV
      WRITE(11,102)VAPRES
      WRITE(11,103)CRPRES
      WRITE(11,104)DPVALV
       WRITE(11,105)CF
      WRITE(11,106)P1
      WRITE(11,110)X
C--- LIQUID OR SUBCOOLED SERVICE
        CV=MDOTL/500/SQRT(RHOL/62.4*DPVALV)
        WRITE(11,113)CV
       ELSE
      END IF
C
C
C
C
C-----FORMATS FOR INPUT AND OUTPUT STATEMENTS---------
   90 FORMAT(3X,I2)
  100 FORMAT(10X,'VALVE CV = ',F6.2)
  101 FORMAT(10X,'LIQUID DENSITY = ',F8.3,' LBM/FT**3')
  102 FORMAT(10X,'VAPOR PRESSURE = ',F8.3,' PSIA')
  103 FORMAT(10X,'CRITICAL PRESSURE = ',F8.3,' PSIA')
  104 FORMAT(10X,'VALVE DELTA P = ',F8.3,' PSID')
  105 FORMAT(10X,'CF(CRITICAL FLOW FACTOR) = ',F6.2)
  106 FORMAT(10X,'PRESSURE UPSTREAM OF VALVE = ',F8.3,' PSIA')
  107 FORMAT(10X,'CRITICAL FLOW CAVITATION OR FLASHING FLOW EXISTS')
  108 FORMAT(10X,'DELTA P USED IN SIZING FORMULA = ',F6.3,' PSID')
  109 FORMAT(10X,'LIQUID FLOW RATE THRU VALVE = ',F8.3,' LBM/HR')
  110 FORMAT(10X,'UPSTREAM FLUID QUALITY = ',F6.3)
  111 FORMAT(10X,'VAPOR DENSITY = ',F8.3,' LBM/FT**3')
  112 FORMAT(10X,'FLOW IS SUBCRITICAL ACROSS VALVE')
  113 FORMAT(10X,'REQUIRED VALVE CV = ',F9.4)
  114 FORMAT(10X,'LIQUID SERVICE')
  216 CONTINUE
      CLOSE(UNIT=10)
      CLOSE(UNIT=11)
      STOP
      END
```

V2 49-1-116 Rev 0
Pg 19 of 2[illegible]

two-phase flow

The two-phase flow formulas, shown below, assume finely divided liquid particles in vapor moving at the same velocity. If insufficient vapor exists entering the valve, the flashing formula on page 3 will prevail.

C_f - pg 7

Therefore:

when $C_f^2 \, \Delta P_1 < \Delta P \left(\frac{w_1}{62.4 G_f} \right)$, use flashing formula on page 3.

ENGLISH FORMULAS:

A. Liquid And Non-Condensable Gas Entering Valve
If there is no vaporization of the liquid and if flow velocity assures a turbulent well-mixed stream.

$$C_v = \frac{W}{44.8 \sqrt{\Delta P \, (w_1 + w_2)}}$$

B. Liquid And Its Vapor Entering Valve
Additional vaporization of liquid occurs. If flow velocity assures a turbulent well-mixed stream.

$$C_v = \frac{W}{63.3 \sqrt{\Delta P \, w_1}}$$

Where:

$$\text{Max. } \Delta P \text{ For Sizing} = C_f^2 \left(\frac{P_1}{2} \right)$$

w_1 = Upstream specific, weight lb/cu. ft. calculated from weight fraction of gas or vapor in the stream X_g and specific volumes of gas or vapor and liquid at upstream pressure V_{g1} and V_f.

$$w_1 = \frac{1}{V_1} = \frac{1}{X_g (V_{g1} - V_f) + V_f}$$

w_2 = Downstream specific weight, lb/cu. ft. calculated using downstream gas specific volume V_{g2}.

$$w_2 = \frac{1}{V_2} = \frac{1}{X_g (V_{g2} - V_f) + V_f}$$

METRIC FORMULAS:

A. Liquid And Non-Condensable Gas Entering Valve

$$C_v = \frac{51.8 \, W}{\sqrt{\Delta P \, (w_1 + w_2)}}$$

B. Liquid And Its Vapor Entering Valve

$$C_v = \frac{36.6 \, W}{\sqrt{\Delta P \, w_1}}$$

Where:

w_1 = Upstream specific weight, (kg/m³)

w_2 = Downstream specific weight, (kg/m³)

compressibility

For many real gases subjected to commonly encountered temperatures and pressures the perfect gas laws are not satisfactory for flow measurement accuracy and correction factors must be used (Ref. 9).

Following conventional flow measurement practice, the compressibility factor Z in the equation $pv = ZRT$ will be used. Z can usually be ignored below 100 psi for common gases.

The value of Z does not differ materially for different gases when correlated as a function of the reduced temperature and reduced pressure, T_r and P_r, respectively and found from Figure 2 and 3.

Figure 2 is an enlargement of a portion of Figure 3. Values taken from these figures are probably accurate to approximately plus or minus two percent.

To obtain the value of Z for a pure substance the reduced pressure and reduced temperature are calculated as the ratio of the actual absolute gas pressure and the corresponding critical absolute temperature and the corresponding critical absolute pressure and absolute critical temperature respectively (page 16).

The compressibility factor Z may be used directly in the volumetric gas formula as shown below:

ENGLISH UNITS $$C_v = \frac{Q \sqrt{GTZ}}{834 \, C_f \, P_1 \, (y - 0.148 \, y^3)}$$

METRIC UNITS $$C_v = \frac{Q \sqrt{GTZ}}{257 \, C_f \, P_1 \, (y - 0.148 \, y^3)}$$

■ English Units
■ Metric Units

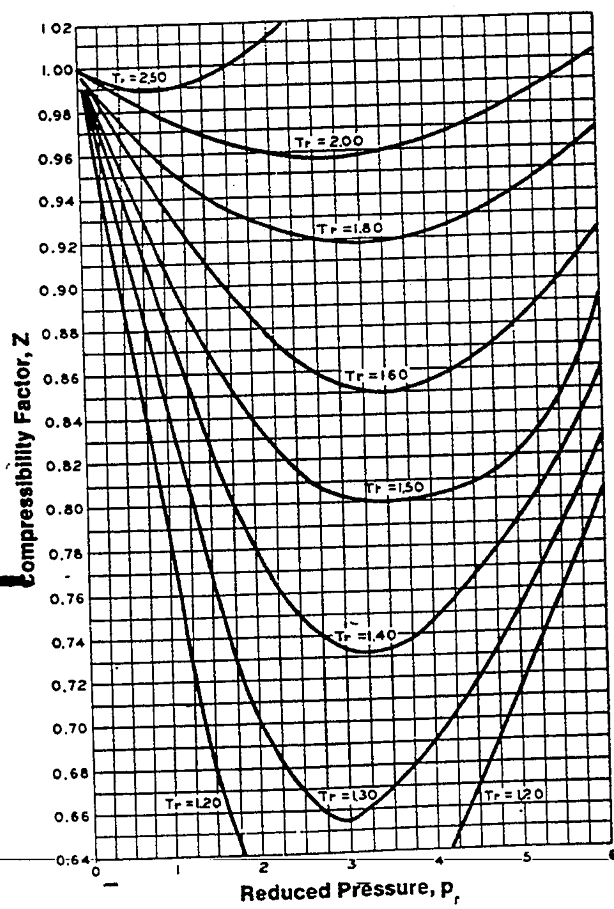


Figure 2
Compressibility Factors for Gases with Reduced Pressures from 0 to 6
(Data from the charts of L. C. Nelson and E. F. Obert, Northwestern Technological Institute)

1040-1-116, Rev 0
Pg 20 of 21

control valve sizing formulas

For Liquid Service

ENGLISH FORMULAS:

A. Subcritical Flow

$\Delta P < C_f^2 (\Delta P_s)$

Volumetric Flow

$$C_v = q\sqrt{\frac{G_f}{\Delta P}}$$

Flow by Weight

$$C_v = \frac{W}{500\sqrt{G_f\,\Delta P}}$$

B. Critical Flow cavitation or flashing

$\Delta P \geq \cancel{C_f^2 (\Delta P_s)}$

$$C_v = \frac{q}{C_f}\sqrt{\frac{G_f}{\Delta P_s}}$$

$$C_v = \frac{W}{500\,C_f\sqrt{G_f\,\Delta P_s}}$$

METRIC FORMULAS:

A. Subcritical Flow

$\Delta P < C_f^2 (\Delta P_s)$

Volumetric Flow

(Ref. 1) $$C_v = 1.16q\sqrt{\frac{G_f}{\Delta P}}$$

Flow by Weight

$$C_v = \frac{1.16\,W}{\sqrt{G_f\,\Delta P}}$$

B. Critical Flow cavitation or flashing

$\Delta P \geq C_f^2 (\Delta P_s)$

$$C_v = \frac{1.16q}{C_f}\sqrt{\frac{G_f}{\Delta P_s}}$$

$$C_v = \frac{1.16\,W}{C_f\sqrt{G_f\,\Delta P_s}}$$

(Ref. 2)
(Ref. 7)

$$^{*}\Delta P_s = P_1 - \left(0.96 - 0.28\sqrt{\frac{P_v}{P_c}}\right)P_v$$

or for simplicity, if $P_v < 0.5\,P_1$, $\Delta P_s = P_1 - P_v$

Where:

- C_v = Valve flow coefficient
- C_f = Critical flow factor (page 7) = †F_L
- G_f = Specific gravity at flowing temperature $= \frac{f_L}{f_{w\,60°F}}$ (water = 1 @ 60° F)
- P_1 = Upstream pressure, psia
- P_2 = Downstream pressure, psia
- P_c = Pressure at thermodynamic critical point, psia (see table, page 4)
- P_v = Vapor pressure of liquid at flowing temperature, psia
- ΔP = Actual pressure drop $P_1 - P_2$, psi
- q = Liquid flow rate, U.S. gpm
- W = Liquid flow rate, pounds per hour

$$^{*}\Delta P_s = P_1 - \left(0.96 - 0.28\sqrt{\frac{P_v}{P_c}}\right)P_v$$

or for simplicity, if $P_v < 0.5\,P_1$, $\Delta P_s = P_1 - P_v$

Where:

- C_v = Valve flow coefficient
- C_f = Critical flow factor (page 7) = †F_L
- G_f = Specific gravity at flowing temperature (water = 1 @ 15° C)
- P_1 = Upstream pressure, bars absolute
- P_2 = Downstream pressure, bars absolute
- P_c = Pressure at thermodynamic critical point, bars absolute (see table, page 4)
- P_v = Vapor pressure of liquid at flowing temperature, bars absolute
- ΔP = Actual pressure drop $P_1 - P_2$, bars
- q = Liquid flow rate, m^3/hr
- W = Liquid flow rate, 1000 kg per hr

Note: 1 bar = 1.02 kg/cm^2

Special considerations (see following pages)

a. cavitation in control valves (page 10)
b. high viscosity, laminar flow (page 14)
c. effect of pipe reducers (page 11)
d. two-phase flow (page 15)

*~~NOTE: $C_f^2\Delta P_s$ is the maximum ΔP~~ for sizing purposes. A valve is not limited in application to this pressure drop, but at higher pressure differential, choked flow will occur without increase in flow rate.
This formula for ΔP_s is sufficiently accurate for general use on liquids.

†**ISA Formulas:** The working equations on this page are entirely compatible with the general formulas shown in ISA SP39.1, "Control Valve Sizing Equations for Incompressible Fluids."

V049-1-116, Rev 0
Pg 21 of 21

English Units
Metric Units