Cryostat Filling Limitations for Proposed Ar Dewar Pressure Increase

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Checked by [signature]

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In order to significantly decrease the amount of time required to fill the cryostats, it is desired to raise the setpoint of the "operating" relief valve on the argon storage dewar to 20 psig from its existing 16 psig setting. This additional pressure increases the flow to the cryostats and will overwhelm the relief capacity if the temperature of the modules within these vessels is warm enough. Using some conservative assumptions and simple calculations within this note, the maximum average temperature that the modules within each cryostat can be at prior to filling from the storage dewar with liquid argon is at least 290 K.

Some Assumptions Used in the Analysis

1. Pressure in the argon storage dewar is at 20 psig.

2. The flow to the ECN cryostat is the most hazardous due to greater limitations on venting (see attached calculations).

3. The maximum flow of argon to the cryostat is 12.3 gpm (see attached calculations).

4. Gaseous nitrogen is concurrently flowing in the vent piping at a rate of 4861 lb/hr, this is derived from both ECS and CC cooling at their maximum rate and ECN condenser attempting to maintain pressure at its maximum.

5. Mixture mass flows are at the maximum at junction of relief devices on ECN(gN_2 mass flow actually increases gradually at junctions toward the ECS).

6. The temperature increase in the vent piping is negligible (large majority of piping is insulated).

7. All flows are treated as incompressible fluids (max. Mach No. = 0.2).

8. Temperature of the gaseous nitrogen prior to mixing in the vent manifold is 84 K, saturated property at 2 atm.

9. Flow equations apply to weight-averaged mixture densities and viscosities.

10. All liquid argon flashes to the bulk module temperature in the cryostat prior to entering the piping.

Explanation of Methodology

The basic purpose of the spreadsheet was to provide a complete model so that the maximum bulk temperature of the modules (line 2) could be determined. The maximum flow of argon to the ECN (line 3) was calculated separately and included after the spreadsheet. A number was picked as a guess for the bulk temperature (line 2). Then a number was picked as a guess for the percent of mass flow to the relief valve (line 18). The actual flow through the relief valve (line 98) was determined using the total flow and the percent of flow to the relief valve. The pressure drops across the inlet and outlets of the relief devices were then calculated. This allowed the calculation of the pressure drops across the relief valve and rupture disk. The various properties of argon were taken from tables at the bulk temperature of the modules.

The section "ΔP Across Relief Valve" calculated the maximum theoretical flow of argon through the relief valve (line 108). Then the theoretical percent of relief flow (line 109) was calculated based on the theoretical relief valve flow divided by the total flow through both the relief valve and rupture disk. The number guessed for the percent of flow to the relief valve (line 18) was then adjusted by iteration until it was close to, but not greater than, the theoretical value (line 109). At this point, the relief valve was operating near its full capacity, which could be checked by noting that the actual flow (line 98) was close to the maximum theoretical flow (line 108).

The next step was to examine the section "ΔP Across Rupture Disk". All of the total argon flow not going though the relief valve would be flowing through the rupture disk. In order to insure that the rupture disk could handle the flow, the maximum theoretical rupture disk flow (line 181) was calculated, and compared to the actual flow (line 182). The actual flow had to be under the maximum theoretical flow, but should be close to the maximum value to obtain the highest total flow. In the case that the actual flow was calculated to be higher than the maximum theoretical flow, the bulk temperature was lowered. Using the new temperature, the first set of iterations was repeated to determine the percent of flow to the relief valve, and the rupture disk flow was compared again. The temperature was lowered through iteration until an acceptable value was found.

Note that the sections on pressure drops were only needed to calculate inlet and outlet pressures for the relief valve and rupture disk. Other sections calculated the changes in various properties of the argon at certain points. Each time the temperature was changed, the values for density and viscosity were changed to reflect the new temperature. The maximum flow of nitrogen from the condensers was also accounted for, since it had an effect on the pressure drops of the outlets of the relief devices.

Notes on Maximum Module Temperature Calculation

*> means that this value is to be re-entered each time the bulk module temperature is changed.

> means that this value is a number, not a formula, but should only be entered once, i.e., it doesn't need to change with the temperature.

(conv.) means that this value is the same as a previous value, but converted to different units.

EN-263, Russ Rucinski, should be referred to for pressure drop calculations.

General Procedure:

In the first section, "Conversion of Liquid to Gas at Module Temp.," enter the bulk temperature of the modules. This is also the temperature that will be used for pressure drops in the relief and rupture disk inlets, and for the relief devices themselves. Enter the gas density at 2.2 bars and 2.4 bars, and at the bulk temperature, so that the density at the cryostat pressure can be calculated. Enter some percent of mass flow to the relief valve. This will be used to assume some mass flow to each relief device for pressure drop calculations. It will be adjusted by iteration later.

In the next section, "ΔP Across Relief Valve Inlet," enter the viscosity at 2.4 bars (or 2.375 bars for more accuracy) and the bulk temperature. The rest of the section is calculated.

The next section, "ΔP Across Rupture Disk Inlet," needs no entries, since it assumes the same gas properties as the previous section.

The section, "ΔP Across Relief Valve Outlet" requires the gas density, and the viscosity at an verge pressure of 2 bars and at the bulk temperature. This just accounts for the drop in pressure to about 1.5 bars. If more accuracy is required, the new pressure could be calculated by adding the common outlet pressure drops to atmospheric pressure.

The "ΔP Across Rupture Disk Outlet" section is completely calculated, based on the assumption that the gas properties remain the same as for the relief valve outlet.

The next section, "Change in Gas at Common Outlet to Outside" reflects the change in properties of the fluid at the junction of the relief device outlets due to the mixing of argon from the relief devices and nitrogen from the condensers.

The "ΔP Across Relief Valve" is completely calculated (ref.1, 3). The specific heat ratio, k, has been determined using the C_p and C_v at the correct temperature and pressure. Also, the flowing temperature is converted from the original bulk temperature, to the equivalent Rankine temperature. The basic purpose of this section is to compare the "Theoretical Percent of Relief Flow" to the actual percent that was entered in section 1. Since the theoretical percent of the relief flow is the maximum flow possible at the given inlet and outlet parameters, this number should be checked such that it does not fall below the "guessed" percentage in the first section of calculations.

The "ΔP Across Common Outlet to Platform" is calculated based on the properties from the "Change in Gas..." section. Also, all pressure drop calculations are based on a equation which relates the friction factor, f, to the Reynolds number and the relative roughness, e/D. The "Friction Factor Guess" is based on an equation in Introduction to Fluid Mechanics (ref.1) and that value is used in another equation in the same reference to find the actual friction factor. Calculations to determine equivalent lengths and relative roughness were based on dimensions from sketches and drawings of the ECN piping and platform manifold.

The section on the "ΔP from Platform Bayonet to Outside" is completely calculated like the previous section, but with a different diameter and equivalent length.

The "Summation of Equivalent ΔPs" is basically a summary of the pressure drops, where the "Rupture Disk Pressure Drop" is calculated based on the three relief valve values, and the rupture disk inlet and outlet values.

The "ΔP Across Rupture Disk Device" is calculated like the relief valve. The complete equation for the "Gas Flow Constant for Subsonic Flow (C1)" is found in reference 2. The specific heat ratio, k, was adjusted according to the actual pressure and temperature. In both the relief valve and the rupture disk, the outlet pressure should be compared to the critical pressure, which it must exceed for the flow to be subsonic. In all cases analyzed, the flow was subsonic.

Conclusions and Recommendations

The average temperature of the module mass for any of the three cryostats can be as high as 290 K prior to filling that particular cryostat. This should not be confused with the average temperature of a single type or location which is useful in protecting the modules-not necessarily the vessel itself. A few modules of each type and at different elevations should be used in an average which would account for the different weights of each module. Note that at 290 K, the actual flow of argon through the relief valve and the rupture disk was under the maximum theoretical flows for each relief device. This means that the bulk temperature could actually have been raised to flow argon through the reliefs at their maximum capacity. Therefore, the temperature of 290 K is a conservative value for the calculated flow rate of 12.3 gpm.

Safeguards in addition to and used in conjunction with operating procedures shall be implemented in such a way so that the above temperature limitation is not exceeded and such that it is exclusive of the programmable logic controller (PLC). One suggestion is using a toggle switch for each cryostat mounted in the PLC I/O box which would maintain control of the signals to open the cold fill valves of each cryostat.

With the safeguards in place while carefully monitoring the temperatures during a cooldown cycle in each cryostat, the set pressure in the argon storage dewar can safely be increased to 20 psig.

References

1. Introduction to Fluid Mechanics, 3rd Ed., Robert W. Fox, Alan T. McDonald, JohnWiley&Sons, 1985.

2. "Fike Technical Bulletin TB 8102, Rupture Disk Sizing", Fike Metal Products Corp.

3. "Catalog 1900-Series 90 Safety Relief Valves", Anderson, Greenwood & Co., 1980.

4. "DØ CC Pressure Vessel and Vacuum Vessel Safety Note", DØ Engineering Note #3740-EN-263, R. Rucinski/R. Luther, Nov., 1990.

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
1	Conversion of Liquid to Gas at Module Temp.			Units
2	*> Bulk Temp. of Modules	290	290	K
3	> Max. Flow of Liquid Argon to Cryostat	12.3	12.3	gpm
4	> Pressure in Cryostat	19.75	19.75	psig
5	Pressure in Cryostat (conv.)	=(B4/14.696+1)*1.01325	2.375	bars
6	> lAr Density @ 2.2 bars	1.342421	1.34	g/cc
7	> lAr Density @ 2.4 bars	1.335861	1.34	g/cc
8	lAr Density @ 2.375 bars	=(B5-2.2)/0.2*(B7-B6)+B6	1.337	g/cc
9	*> gAr Density @ 2.2 bars	3.655	3.655	mg/cc
10	*> gAr Density @ 2.4 bars	3.987	3.987	mg/cc
11	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	3.945	mg/cc
12	gAr Density @ 2.375 bars (conv.)	=B11/1000*62.428	0.246	lbm/ft^3
13	Maximum Flow of Argon Gas	=B3*B8/B11*1000	4167	gpm
14	Maximum Flow of Argon Gas (conv.)	=B13*0.13368	557	cfm
15	Air Equivalent Flow @STP	=6.32*B17*356/B16*SQRT(B99/(520*B177*28.97))	1443	scfm air
16	Specific Heat Constant, C, for Ar	=520*SQRT(B168*(2/(B168+1))^((B168+1)/(B168-1)))	378	
17	Max. Mass Flow of Argon Gas	=B14*B12*60	8232	lbm/hr
18	*> Percent of Mass Flow to Relief Valve	0.48	0.48	
19				
20	ΔP Across Relief Valve Inlet			Units
21	> Inner Pipe Diameter	0.206	0.206	ft
22	Inner Pipe Diameter (conv.)	=B21*12	2.472	in
23	> Equivalent Length	38	38	ft
24	Ar Gas Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	3.945	mg/cc
25	Ar Gas Density @ 2.375 bars (conv.)	=B24/1000*62.428	0.246	lbm/ft^3
26	*> gAr Viscosity @ 2.4 bars & Temp.	0.0002228	0.0002228	g/cm-s
27	gAr Viscosity @ 2.4 bars (conv.)	=B26*100	0.02228	centipoise
28	Max. Mass Flow to Relief Valve	=B17*B18	3952	lbm/hr
29	Reynolds Number	=6.31*B28/(B22*B27)	453000	
30	> Relative Roughness (e/D)	0.0007	0.0007	
31	Friction Factor Guess	=0.25*(LOG(B30/3.7+5.74/(B29^0.9)))^-2	0.019	
32	Friction Factor	=0.25*(LOG(B30/3.7+2.51/(B29*B31^0.5)))^-2	0.0189	
33	Pressure Drop	=0.00000336*B32*B23*(B28^2)/B25/(B22^5)	1.655	psi
34				

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
35	ΔP Across Rupture Disk Inlet			Units
36	Inner Pipe Diameter (conv.)	=B37/12	0.172	ft
37	> Inner Pipe Diameter	2.067	2.067	in
38	> Equivalent Length	49	49	ft
39	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	3.945	mg/cc
40	gAr Density @ 2.375 bars (conv.)	=B39/1000*62.428	0.246	lbm/ft^3
41	gAr Viscosity @ 2.4 bars	=B26	0.0002228	g/cm-s
42	gAr Viscosity @ 2.4 bars (conv.)	=B41*100	0.02228	centipoise
43	Max. Mass Flow to Rupture Disk	=B17*(1-B18)	4281	lbm/hr
44	Reynolds Number	=6.31*B43/(B37*B42)	587000	
45	> Relative Roughness (e/D)	0.0009	0.0009	
46	Friction Factor Guess	=0.25*(LOG(B45/3.7+5.74/(B44^0.9)))^-2	0.0198	
47	Friction Factor	=0.25*(LOG(B45/3.7+2.51/(B44*B46^0.5)))^-2	0.0197	
48	Pressure Drop	=0.00000336*B47*B38*(B43^2)/B40/(B37^5)	6.394	psi
51				
52	ΔP Across Relief Valve Outlet			Units
53	Inner Pipe Diameter (conv.)	=B54/12	0.272	ft
54	> Inner Pipe Diameter	3.26	3.26	in
55	> Equivalent Length	51	51	ft
56	*> gAr Density @ 2.0 bar & Temp.	3.324	3.324	mg/cc
57	gAr Density @ 2.0 bar (conv.)	=B56/1000*62.428	0.208	lbm/ft^3
58	*> gAr Viscosity @ 2.0 bar & Temp.	0.0002227	0.0002227	g/cm-s
59	gAr Viscosity @ 2.0 bar (conv.)	=B58*100	0.02227	centipoise
60	Max. Mass Flow to Relief Valve	=B28	3952	lbm/hr
61	Reynolds Number	=6.31*B60/(B54*B59)	343000	
62	> Relative Roughness (e/D)	0.00055	0.00055	
63	Friction Factor Guess	=0.25*(LOG(B62/3.7+5.74/(B61^0.9)))^-2	0.0185	
64	Friction Factor	=0.25*(LOG(B62/3.7+2.51/(B61*B63^0.5)))^-2	0.0183	
65	Pressure Drop	=0.00000336*B64*B55*(B60^2)/B57/(B54^5)	0.642	psi
66				

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
67	ΔP Across Rupture Disk Outlet			Units
68	Inner Pipe Diameter (conv.)	=B69/12	0.18	ft
69	> Inner Pipe Diameter	2.157	2.157	in
70	> Equivalent Length	1.75	1.75	ft
71	gAr Density @ 2.0 bar & Temp.	=B56	3.324	mg/cc
72	gAr Density @ 2.0 bar (conv.)	=B71/1000*62.428	0.208	lbm/ft^3
73	gAr Viscosity @ 2.0 bar & Temp.	=B58	0.0002227	g/cm-s
74	gAr Viscosity @ 2.0 bar (conv.)	=B73*100	0.02227	centipoise
75	Max. Mass Flow to Rupture Disk	=B43	4281	lbm/hr
76	Reynolds Number	=6.31*B75/(B69*B74)	562000	
77	> Relative Roughness (e/D)	0.0009	0.0009	
78	Friction Factor Guess	=0.25*(LOG(B77/3.7+5.74/(B76^0.9)))^-2	0.0198	
79	Friction Factor	=0.25*(LOG(B77/3.7+2.51/(B76*B78^0.5)))^-2	0.0197	
80	Pressure Drop	=0.00000336*B79*B70*(B75^2)/B72/(B69^5)	0.219	psi
81				
82	Change in Gas at Common Outlet to Outside			Units
83	Pressure in Cryostat	=B4	19.75	psig
84	Pressure in Cryostat (conv.)	=(B83/14.696+1)*1.01325	2.375	bars
85	gAr Density @ 2.2 bars	=B9	3.655	mg/cc
86	gAr Density @ 2.4 bars	=B10	3.987	mg/cc
87	gAr Density @ 2.375 & Temp.	=(B84-2.2)/0.2*(B86-B85)+B85	3.945	mg/cc
88	Temp. at Common Outlet	=(B2*B17+84*B189)/(B17+B189)	214	K
89	> Pressure to Calculate Density	1.5	1.5	bars
90	*> gAr Density @ 1.5 bars & New Temp.	3.396	3.396	mg/cc
91	*> gAr Viscosity @ 1.5 bars & New Temp.	0.0001696	0.0001696	g/cm-s
92	gAr Viscosity @ 1.5 bar (conv.)	=B91*100	0.01696	centipoise
93				

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
94	ΔP Across Relief Valve			Units
95	> Critical Ratio (Pcr/P1) for Argon	0.487	0.487	
96	> Specific Heat Ratio (k) for Argon	=B168	1.67	
97	> Area of 2" x 3" Relief Valve	2.29	2.29	in^2
98	Flow Through Relief Valve	=B28	3952	lbm/hr
99	Flowing Temperature	=1.8*B2	522	deg R
100	> Compressibility Factor	1	1	
101	> Nozzle Coefficient for type 93T	0.939	0.939	
102	Flowing Inlet Pressure (P1)	=B4+14.696-B33	32.79	psia
103	> Molecular Weight of Argon	39.948	39.95	g/mol
104	Critical Pressure (Pcr)	=B95*B102	15.97	psia
105	Outlet Pressure (P2) (using delta p's)	=14.696+B154+B133+B65	27.39	psia
106	Pressure Ratio (P2*/P1)	=(B102-0.55*((B102-B105)^0.98))/B102	0.912	
107	Theoretical Factor (F*) (using P2)	=SQRT((B96/(B96-1))*(B106^(2/B96)-B106^((B96+1)/B96)))	0.284	
108	Max. Theoretical Relief Flow (using F*)	=735*B97*B101*B102*B107*SQRT(B103/B99/B100)	4072	lbm/hr
109	Theoretical Percent of Relief Flow	=B108/B17	0.4947	
110	Pressure Drop Across Relief Valve	=B102-B105	5.403	psi
111				

Maximum Module Temperature Calculation 10/17/91

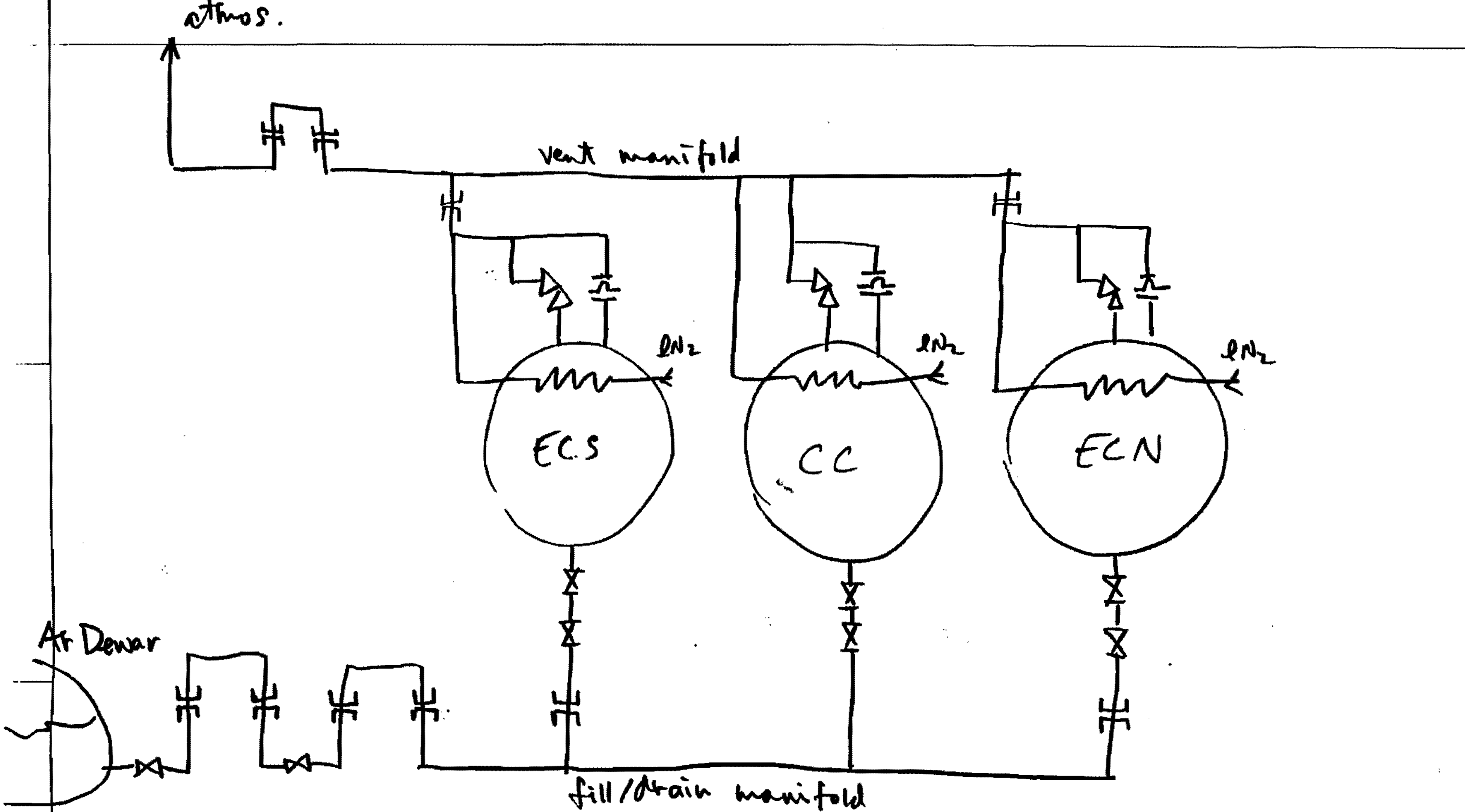
	A	B	C	D
112	ΔP Across Common Outlet to Platform Bayonet			Units
113	> Inner Pipe Diameter	0.355	0.355	ft
114	Inner Pipe Diameter (conv.)	=B113*12	4.26	in
115	> Equivalent Length	273	273	ft
116	gAr Density @ 1.5 bar & New Temp.	=B90	3.396	mg/cc
117	gAr Density @ 1.5 bar (conv.)	=B116/1000*62.428	0.212	lbm/ft^3
118	*> gN2 Gas Density @ 1.5 bar & New Temp.	2.411028	2.411	mg/cc
119	gN2 Gas Density @ 1.5 bar (conv.)	=B118/1000*62.428	0.151	lbm/ft^3
120	Gas Mixture Density @1.5 bar	=(B17*B117+B127*B119)/B128	0.189	lbm/ft^3
121	gAr Viscosity @ 1.5 bar & New Temp.	=B91	0.0001696	g/cm-s
122	gAr Viscosity @ 1.5 bar (conv.)	=B121*100	0.01696	centipoise
123	*> gN2 Viscosity @ 1.5 bar & New Temp.	0.000136454	0.0001365	g/cm-s
124	gN2 Viscosity @ 1.5 bar (conv.)	=B123*100	0.01365	centipoise
125	Mixture Viscosity @1.5 bar	=(B17*B122+B127*B124)/B128	0.01573	centipoise
126	Max. Mass Flow of Argon Gas	=B17	8232	lbm/hr
127	Max. Flow of Nitrogen Gas	=B189	4861	lbm/hr
128	Mass Flow of Mixture	=B126+B127	13093	lbm/hr
129	Reynolds Number	=6.31*B128/(B114*B125)	1230000	
130	> Relative Roughness (e/D)	0.0004	0.0004	
131	Friction Factor Guess	=0.25*(LOG(B130/3.7+5.74/(B129^0.9)))^-2	0.0165	
132	Friction Factor	=0.25*(LOG(B130/3.7+2.51/(B129*B131^0.5)))^-2	0.0164	
133	Pressure Drop	=0.00000336*B132*B115*(B128^2)/B120/(B114^5)	9.705	psi
134				

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
135	ΔP from Platform Bayonet to Outside			Units
136	> Inner Pipe Diameter	0.53	0.53	ft
137	Inner Pipe Diameter (conv.)	=B136*12	6.36	in
138	> Equivalent Length	516	516	ft
139	gAr Gas Density @ 1.5 bar & New Temp.	=B90	3.396	mg/cc
140	gAr Gas Density @ 1.5 bar (conv.)	=B139/1000*62.428	0.212	lbm/ft^3
141	gN2 Gas Density @ 1.5 bar & New Temp.	=B118	2.411	mg/cc
142	gN2 Gas Density @ 1.5 bar (conv.)	=B141/1000*62.428	0.151	lbm/ft^3
143	Gas Mixture Density @1.5 bar	=(B17*B140+B189*B142)/B149	0.189	lbm/ft^3
144	gAr Viscosity @ 1.5 bar & New Temp.	=B121	0.0001696	g/cm-s
145	gAr Viscosity @ 1.5 bar (conv.)	=B144*100	0.01696	centipoise
146	gN2 Viscosity @ 1.5 bar & New Temp.	=B123	0.0001365	g/cm-s
147	gN2 Viscosity @ 1.5 bar (conv.)	=B146*100	0.01365	centipoise
148	Gas Mixture Viscosity @1.5 bar	=(B17*B145+B189*B147)/B149	0.01573	centipoise
149	Max. Mass Flow of Gas Mixture	=B128	13093	lbm/hr
150	Reynolds Number	=6.31*B149/(B137*B148)	826000	
151	> Relative Roughness (e/D)	0.00027	0.00027	
152	Friction Factor Guess	=0.25*(LOG(B151/3.7+5.74/(B150^0.9)))^-2	0.0156	
153	Friction Factor	=0.25*(LOG(B151/3.7+2.51/(B150*B152^0.5)))^-2	0.0155	
154	Pressure Drop	=0.00000336*B153*B138*(B149^2)/B143/(B137^5)	2.345	psi
155				
156	Summation of Equivalent ΔPs			Units
157	Relief Valve Inlet Pressure Drop	=B33	1.655	psi
158	Relief Valve Outlet Pressure Drop	=B65	0.642	psi
159	Relief Valve Pressure Drop	=B110	5.403	psi
160	Relief Valve/Disk Branch	=B33+B65+B110	7.7	psi
161	Rupture Disk Inlet Pressure Drop	=B48	6.394	psi
162	Rupture Disk Outlet Pressure Drop	=B80	0.219	psi
163	Rupture Disk Pressure Drop	=B157+B158+B159-B161-B162	1.087	psi
164	Common Outlet Pressure Drop	=B133	9.705	psi
165	Platform to Outside Pressure Drop	=B154	2.345	psi
166				

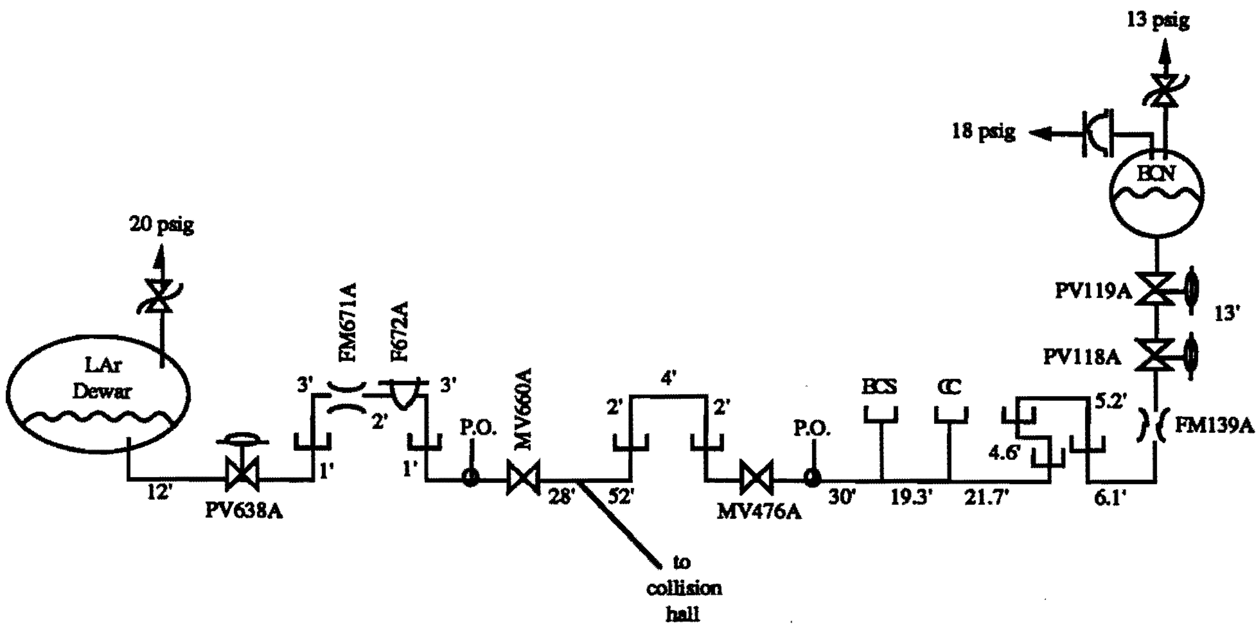
Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
167	ΔP Across Rupture Disk			Units
168	*>Argon Specific Heat Ratio (k)	1.673	1.673	
169	Critical Ratio	=(2/(B168+1))^(B168/(B168-1))	0.486	
170	> Area of 3" Rupture Disk	=3.14159*(3^2)/4	7.069	in^2
171	Flow Through Rupture Disk	=B43	4281	lbm/hr
172	Flowing Temperature	=1.8*B2	522	deg R
173	> ASME Coefficient (K)	0.62	0.62	
174	Pressure Ratio (Pe/Po)	=B179/B176	0.961	
175	gAr Flow Constant for Subsonic Flow(C1)	=SQRT(2*32.2/1545*(B168/(B168-1))*(B174^(2/B168)-B17	0.039	
176	Flowing Inlet Pressure (Po)	=B4+14.696-B48	28.05	psia
177	> Molecular Weight of Argon	39.948	39.948	g/mol
178	Critical Pressure (Pcr)	=B169*B176	13.64	psia
179	Outlet Pressure (Pe) (using delta p's)	=14.696+B154+B133+B80	26.97	psia
180	Pressure Drop Across Rupture Disk	=B176-B179	1.087	psi
181	Maximum Theoretical Rupture Disk Flow	=B170*B173*B175*B176*SQRT(B177/B172)*60*60	4833	lbm/hr
182	Actual Rupture Disk Flow	=B43	4281	lbm/hr
183				
184	Maximum Flow from Condensers			units
185	> Max. Flow of Liquid Nitrogen	13	13	gpm
186	Max. Flow of Liquid Nitrogen (conv.)	=B185/7.48	1.74	ft^3/min
187	Density of LN2 @ 3.5 atm	0.747	0.747	g/cc
188	Density of LN2 (conv.)	=B187*62.4	46.6128	lbm/ft^3
189	Mass Flow of LN2	=B186*B188*60	4861	lbm/hr



Simplified Cryostat Fill/Vent Arrangement

Calculation of Max. Flowrate from LAr Dewar to ECN



d = 1.682 in = 0.1402 ft [1 1/2" SCH. 10 inner pipe dia.]

$A = 0.01543\ ft^2$ [cross-sectional area]

Reference: drawings from Tony Parker	up to cryocorner	cryocorner to CC	CC to ECN	TOTAL
# of elbows, 90°	17	4	19	40
# of elbows, 45°	1	3	1	5
# of tees, branch	3	0	0	3
# of tees, thru	0	2	0	2

Calculation of Equivalent Length

Calculate the equivalent length of the piping from the LAr dewar to the inner vessel of the ECN.

$L_{piping} = L_{1.7\text{" dia.}} + L_{1.0\text{" dia.}}$

Adjust 169 ft length to CC (ref. Kelly Dixon) to include ECN.

$L_{1.7\text{" dia.}}$ = 169 ft (length to CC) - 8.3 ft (CC drain line) + 21.7 ft (CC to rotary bayonet assembly) + 4.6 ft + 5.2 ft (rotary U-tube dimensions) + 6.1 ft + 13 ft (ECN drain line) = 211.3 ft total.

Equivalent lengths of the flowmeters are accounted for by including a 4 foot length of 1.0" diameter piping. Convert 1.0" diameter equivalent length to 1.7" dia. equivalent length:

Reference: Crane Technical Paper No. 410

(1" SCH. 40 to 1 1/2" SCH. 10)

$$L_{1.0\text{" dia.}} = \left(\frac{1.682}{1.049}\right)^5 \times 4' = 42.4'$$

L_{piping} = 211.3 ft + 42.4 ft = 253.7 ft total

Convert elbows and tees into equivalent lengths of pipe.

$L_{fittings}$ = [40(20) + 5(14) + 3(60) + 2(20)] x 0.1402 ft = 152.8 ft

L_{eq} = 253.7 ft + 152.8 ft = **406.5 ft**

Calculation of Resistance Coefficient

Reference: Crane Technical Paper No. 410

Calculate the resistance coefficient for the piping and fittings.

$$K_{piping, fittings} = f\left(\frac{L_{eq}}{d}\right)$$

let f = 0.022 [friction factor guess]

$$K_{piping, fittings} = 0.022\left(\frac{406.5\ ft}{0.1402\ ft}\right) = 63.79$$

Include inlet and outlet losses (ref. Kelly Dixon).

$K_{inlet} = 0.5$

$K_{outlet} = 1.0$

Calculate resistance coefficient for the valves.

$$K_{valves} = \left(\frac{29.9\ d^2}{C_v}\right)^2 \times (\#\ of\ valves) = \left(\frac{29.9\ (1.682)^2}{34}\right)^2 \times 4 = 24.76$$

where the diameter, d, is in inches, not feet.

$\Sigma K = 63.79 + 1.5 + 24.76 = \mathbf{90.05}$

Driving Pressure

Calculate the differential pressure available under relieving conditions.

max. head available = 720.3 ft (dewar @ 16,000 gallons)

- 715.2 ft (bottom of ECN)

5.1 ft (total elevation difference)

Calculate the pressure due to elevation difference.

Density of liquid argon @ 19.75 psig = 1.337 g/cc, which corresponds to a specific weight of 0.580 psi/ft.

Δp due to head = 5.1 ft x 0.580 psi/ft = 2.96 psi

$\Delta p_{relieving}$ = (LAr dewar pressure) - (ECN pressure) + (head pressure)

= 34.7 psia - 34.45 psia + 2.96 psi = 3.21 psid

Determine the pressure drop across the cryofilter.

Actual experience shows that with a 30 gpm flow, the pressure drop across the cryofilter is 4 psid.

$$\Delta p_{filter} = \left(\frac{q}{30}\right)^2 \times 4 \text{ psid} = 0.00444\, q^2$$

where Δp_{filter} is in psid if q is in gpm.

$$\Delta p_{available} = \Delta p_{relieving} - \Delta p_{filter}$$

Calculation of Flowrate

Calculate the flowrate, q, by rearranging Darcy's formula (ref. Crane 410).

modified Darcy's formula:

$$\Delta p = \frac{\rho\,\Sigma K}{144}\,\frac{v^2}{2\,g_c}$$

where: Δp is in psid,

ρ is in lb_m/ft^3,

and v is in ft/s.

(144 is a conversion factor of in^2/ft^2.)

Rearrange to solve for the velocity, v.

$$v = \sqrt{\frac{2\,g_c(144\,\Delta p)}{\rho\,\Sigma K}} = \sqrt{\frac{2\left(32.174\,\frac{lb_m\text{-}ft}{lb_f\text{-}s^2}\right)\left(144\,\frac{in^2}{ft^2}\right)\Delta p_{available}}{\left(83.47\,\frac{lb_m}{ft^3}\right)(90.05)}}$$

$$v = 1.110\sqrt{\Delta p_{available}}$$

where v is in ft/s if $\Delta p_{available}$ is in psid.

Substitute formulas with q into both sides of the equation for v and Δp.

Substitute for v: (Let Q be the flow rate in cfs.)

$$v = \frac{Q}{A} = \frac{4Q}{\pi d^2} = \frac{4Q}{\pi (0.1402\ \text{ft})^2} = 64.78Q$$

where v is in ft/s if Q is in cfs.

Convert the equation so that v will be in ft/s if q is in gpm.

$$v = 64.78\left(q\ \frac{\text{gal}}{\text{min}}\ \text{x}\ \frac{\text{min}}{60\ \text{sec}}\ \text{x}\ 0.13368\ \frac{\text{ft}^3}{\text{gal}}\right) = 0.1443q$$

where v is in ft/s if q is in gpm.

Substitute for Δp:

From before, $\Delta p_{available} = \Delta p_{relieving} - \Delta p_{filter}$.

$$\Delta p_{available} = 3.21\ \text{psid} - 0.00444q^2$$

where $\Delta p_{available}$ is in psid if q is in gpm.

From before,

$$v = 1.110\sqrt{\Delta p_{available}}$$

where v is in ft/s if $\Delta p_{available}$ is in psid.

Substitute formula for $\Delta p_{available}$ to get v in terms of q.

$$v = 1.110\sqrt{3.21 - 0.00444q^2}$$

where v is in ft/s if q is in gpm.

Set the two equations for v in terms of q equal, and solve for q.

$$v = 0.1443q = 1.110\sqrt{3.21 - 0.00444q^2}$$

$$q = \sqrt{\frac{3.21}{\left(\frac{0.1443}{1.110}\right)^2 + 0.00444}}$$

$$q = \mathbf{12.26 \quad gpm}$$

Check Friction Factor

$$Re_{d_{relieving}} = \frac{\rho V_{rel.} d}{\mu}$$

$$\mu = 2.4185 \times 10^{-3} \frac{g}{cm\text{-}s} \text{ @sat. 1.3 bars} = 1.6252 \times 10^{-4} \frac{lb_m}{ft\text{-}s}$$

$$q_{relieving} = 12.26 \text{ gpm}$$

$$v_{rel.} = \frac{q_{relieving}}{A} = \frac{4\, q_{relieving}}{\pi d^2} = \frac{4\left(12.26 \text{ gpm} \times \frac{1 \text{ cfs}}{448.83 \text{ gpm}}\right)}{\pi\, (0.1402 \text{ ft})^2} = 1.769 \frac{ft}{s}$$

$$Re_{d_{relieving}} = \frac{\left(83.47 \frac{lb_m}{ft^3}\right)\left(1.769 \frac{ft}{s}\right)(0.1402 \text{ ft})}{1.6252 \times 10^{-4} \frac{lb_m}{ft\text{-}s}} = 1.274 \times 10^5$$

Assuming a value of 0.00015 roughness for commercial steel pipe, the relative roughness is 0.001, and the friction factor is 0.022, which checks.

TK Solver Plus Analysis

The following two pages are printouts of the variable and rule sheet from a TK Solver model set up to verify the hand calculations for the maximum flow rate to the ECN from the Argon dewar. The first page is the variable sheet, which shows the typed inputs and calculated outputs for various parameters. The complete solution requires guessing a number for the friction factor. The program then iterates to find the exact solution. Also note that the columns have a set width, so that not all of the entries are shown completely, specifically, g has units of lbm-ft/lbf-s^2. The second sheet is the rule sheet, which shows the various formulas used. The complete model has been saved in the Co-op Mac, under the name "TK LAD Flow to ECN".

St	Input	Name	Output	Unit	Comment
	1.682	D		in	inner pipe dia.
		d	.14016667	ft	inner pipe dia. (converted)
		A	.01543046	ft^2	cross-sectional area
	40	Els90			number of 90° elbows
	5	Els45			number of 45° elbows
	3	TeesBr			number of tees, branch
	2	TeesTh			number of tees, thru
	253.7	Lpiping		ft	equivalent length of 1.7" piping
		Lfittin	152.78167	ft	equivalent length of fittings
		Leq	406.48167	ft	equivalent length
		f	.02195416		friction factor (guess)
	.5	Kinlet			inlet resistance
	1	Koutlet			outlet resistance
		Kpiping	63.66681		resistance of piping
	34	Cv			coeff. of valves
	4	valves			number of valves counted
		Kvalves	24.759878		resistance of valves
		SumK	89.926688		summation of resistances
	5.1	elev		ft	max. head available
	83.47	rho		lbm/ft^3	density of argon
		SpWt	.57965278	psi/ft	specific weight of argon
		DPhead	2.9562292	psi	delta p from head
		DPrel	3.2062292	psi	delta p relieving
		DPfilte	.66797323	psi	delta p from filter
		DPavail	2.5382559	psi	delta p available
		Vrel	1.7701374	ft/s	relieving velocity
		Re	127431.07		Reynold's number
	.00016252	visc		lbm/ft-s	viscosity
	.00015	e			roughness coefficient
		rough	.00107015		relative roughness (e/d)
		pi	3.14159		pi constant
		g	32.174	lbm-ft/lb	gc conversion constant
		q	12.259444	gpm	flow rate

```
S Rule
* pi = 3.14159     "constant for pi
* g = 32.174      "constant for gc, in units of (lbm-ft)/(lbf-s^2)
* d = D/12      "conversion of inner pipe dia. from inches to feet
* A = pi*(d^2)/4      "cross-sectional area of pipe
  Lfittings = d*(Els90*20+Els45*14+TeesBr*60+TeesTh*20)      "equivalent length
* Leq = Lpiping + Lfittings      "total equivalent length of 1.7" dia piping
* Kpiping = f*Leq/d      "resistance coeff. for piping and fittings
* Kvalves = valves*((29.9*(D^2)/Cv)^2)      "resistance of valves
* SumK = Kpiping+Kvalves+Kinlet +Koutlet      "summation of K coeff.
* SpWt = rho/144      "specific weight at correct density
* DPhead = elev * SpWt      "delta p due to max. head pressure
* DPrel = 34.7 - 34.45 + DPhead      "delta p due to elevation difference
* DPfilter = 4*((q/30)^2)      "pressure drop across cryofilter
* DPavail = DPrel - DPfilter      "available differential driving pressure
* DPavail = (rho*SumK*(Vrel^2))/(144*2*g)      "modified Darcy's formula
* Vrel = (q*.13368/60)/A      "velocity in ft/s from flow rate in gpm
* Re = rho*Vrel*d/visc      "Reynold's number for pipe flow
* rough = e/d      "relative roughness for commercial steel of 1 1/2" dia.
* 1/(f^.5) = -2.0*log((rough/3.7) + (2.51/(Re*(f^.5))))      "Moody chart
```

KD 22Jul91

ECN Equivalent Lengths of Relief / Exhaust Piping

① Relief Valve Inlet

$l_e = 38'$, $d = 0.206'$ ref: EN-263

② Rupture Disk Inlet

#els: 8

$l_{pipe} = 51'' + 23 + 5 + 15 = 94'' = 7.8'$

$d = 0.172'$ (2" sch 40)

$l_e = 7.8' + 30(0.172) = 49'$

③ Relief Valve Outlet

#tees (branch) : 1

#els, 90° : 1 (mitered)

#els, 45° : 2 (mitered)

~~lee~~ $d = 0.27'$

$l_e = 1.9' + (60 + 60 + 2(30))(0.27) = 51'$

④ Rupture Disk Outlet

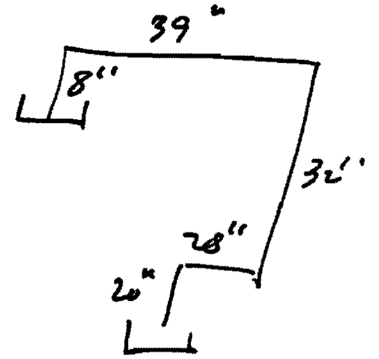
$d = 0.180'$

$l_e = 1.75'$

8) Relief Common Outlet to Platform Bayonet

$d = 0.355'$

length rot. bayonet spool assy



$8'' + 39 + 32 + 28 + 20 = 127''$

$l_{piping} = 24'' + 127'' + 62'' + 2(157.5'') + 38 + 10 + 40$
$+ 67 + 210.5 + 457.5 + 74 + 16$
$= 1441'' = 120\ ft$

\# els, 90°: 11
\# els, 45°: 1 (approx)
\# tees (thru): 2
\# tees (brch): 1

$l_e = 120 + 0.355(11(30) + 2(20) + 1(60))$
$= 120 + 153$
$= 273'$

6) Platform Bayonet to Outside

$d = 0.530'$
$l_e = 516'$

Ref. EN263

Determine Worst Case Cryostat to Fill Due to Pressure

Fill capacity

Reference: ECN numbers taken from previous "Calculation of Max. Flowrate from LAr Dewar to ECN".

$$\left(q_{fill}^{ECN}\right)_{max} = 12.3 \text{ gpm}$$

$$\Sigma K^{ECN} = 90.05$$

$$\Sigma K^{CC} = \Sigma K^{ECN} - \frac{f(L_{eq})}{d} \cong 90.05 - \frac{(0.022)(30\text{ ft})}{0.1402\text{ ft}} = 85.34$$

$$\Sigma K^{ECS} = \Sigma K^{CC} - \frac{f(L_{eq})}{d} \cong 85.34 - \frac{(0.022)(27\text{ ft})}{0.1402\text{ ft}} = 81.10$$

The ECS has the smallest resistance coefficient because it has the shortest equivalent length of piping from the argon dewar. Therefore, the same driving pressure from the dewar will produce the largest inlet flow to the ECS. The flowrate is inversely proportional to the square root of the resistance coefficient:

$$q^{cryostat} \propto \frac{1}{\sqrt{\Sigma K^{cryostat}}}$$

Therefore, the flowrates of the ECS and ECN can be compared as follows:

$$\frac{q_{fill}^{ECS}}{q_{fill}^{ECN}} = \frac{\sqrt{\Sigma K^{ECN}}}{\sqrt{\Sigma K^{ECS}}} = \frac{\sqrt{90.05}}{\sqrt{81.10}} = 1.054$$

The maximum inlet flow to the ECS is greater than the maximum inlet flow to the ECN by about 5%. However, the ECS is not the worst case cryostat to fill because it also has a shorter equivalent length of relief piping.

Venting capacity

Reference: DØ Engineering Note 3740.224-EN-323, ECN Pressure and Vacuum Vessel Engineering Notes.

The first spreadsheet in EN-323 calculates the ECN relief flow capacity. In the section, "ΔP Across Relief Valve", line 108 shows the maximum theoretical flow through the relief valve. In the section, "ΔP Across Rupture Disk", line 181 shows the maximum theoretical flow through the rupture disk. Therefore, the total mass flow can be calculated as:

$$\rho\left(q_{rel}^{ECN}\right)_{max} = 7740\,\frac{lb_m}{hr}\,(\text{relief valve}) + 7458\,\frac{lb_m}{hr}\,(\text{rupture disk}) = 15{,}198\,\frac{lb_m}{hr}$$

Note that q here represents the flow through the relief piping, out of the ECN, whereas the q on the previous page represented the inlet fill piping, into the ECN.

The calculation of the venting capacity of the ECS is more complicated, because the numbers can not be referenced from EN-323. To calculate the ECS capacity, the ECN spreadsheet was modified for the ECS, changing the section, "ΔP Across Common Outlet to Cryocorner". Line 115 is the equivalent length of this section of piping. ECN had an equivalent length of 273 ft, which was calculated in this note (see previous K. Dixon's hand calculations, "ECN Equivalent Lengths of Relief/Exhaust Piping"). The only difference in the relief piping of the ECS is that the equivalent length of the common outlet changes to 238 ft. Using this new equivalent length, the spreadsheet was re-calculated to find the maximum theoretical flows through the relief valve and rupture disk. The following pages show the actual spreadsheet, modified for the ECS.

Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
1	Conversion of Liquid to Gas at Module Temp.			Units
2	> Bulk Temp. of Modules	96	96	K
3	>* Max. Liquid Equivalent Flow of Argon to Reliefs	24.9	24.9	gpm
4	> Pressure in Cryostat	19.75	19.75	psig
5	Pressure in Cryostat (conv.)	=(B4/14.696+1)*1.01325	2.375	bars
6	> lAr Density @ 2.2 bars	1.342421	1.342	g/cc
7	> lAr Density @ 2.4 bars	1.335861	1.336	g/cc
8	lAr Density @ 2.375 bars	=(B5-2.2)/0.2*(B7-B6)+B6	1.337	g/cc
9	> gAr Density @ 2.2 bars	11.77	11.77	mg/cc
10	> gAr Density @ 2.4 bars	12.75	12.75	mg/cc
11	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	12.627	mg/cc
12	gAr Density @ 2.375 bars (conv.)	=B11/1000*62.428	0.788	lbm/ft^3
13	Maximum Flow of Argon Gas	=B3*B8/B11*1000	2636	gpm
14	Maximum Flow of Argon Gas (conv.)	=B13*0.13368	352	cfm
15	Air Equivalent Flow @STP	=6.32*B17*356/B16*SQRT(B99/(520*B177*28.97))	1658	scfm air
16	Specific Heat Constant, C, for Ar	=520*SQRT(B168*(2/(B168+1))^((B168+1)/(B168-1)))	383	
17	Max. Mass Flow of Argon Gas	=B14*B12*60	16666	lbm/hr
18	*> Percent of Mass Flow to Relief Valve	0.474	0.474	
19				
20	ΔP Across Relief Valve Inlet			Units
21	> Inner Pipe Diameter	0.206	0.206	ft
22	Inner Pipe Diameter (conv.)	=B21*12	2.472	in
23	> Equivalent Length	38	38	ft
24	Ar Gas Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	12.627	mg/cc
25	Ar Gas Density @ 2.375 bars (conv.)	=B24/1000*62.428	0.788	lbm/ft^3
26	> gAr Viscosity @ 2.4 bars & Temp.	0.0000803	0.0000803	g/cm-s
27	gAr Viscosity @ 2.4 bars (conv.)	=B26*100	0.00803	centipoise
28	Max. Mass Flow to Relief Valve	=B17*B18	7900	lbm/hr
29	Reynolds Number	=6.31*B28/(B22*B27)	2510000	
30	> Relative Roughness (e/D)	0.0007	0.0007	
31	Friction Factor Guess	=0.25*(LOG(B30/3.7+5.74/(B29^0.9)))^-2	0.0183	
32	Friction Factor	=0.25*(LOG(B30/3.7+2.51/(B29*B31^0.5)))^-2	0.0182	
33	Pressure Drop	=0.00000336*B32*B23*(B28^2)/B25/(B22^5)	1.993	psi
34				

Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
35	ΔP Across Rupture Disk Inlet			Units
36	Inner Pipe Diameter (conv.)	=B37/12	0.172	ft
37	> Inner Pipe Diameter	2.067	2.067	in
38	> Equivalent Length	49	49	ft
39	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	12.627	mg/cc
40	gAr Density @ 2.375 bars (conv.)	=B39/1000*62.428	0.788	lbm/ft^3
41	gAr Viscosity @ 2.4 bars	=B26	0.0000803	g/cm-s
42	gAr Viscosity @ 2.4 bars (conv.)	=B41*100	0.00803	centipoise
43	Max. Mass Flow to Rupture Disk	=B17*(1-B18)	8766	lbm/hr
44	Reynolds Number	=6.31*B43/(B37*B42)	3330000	
45	> Relative Roughness (e/D)	0.0009	0.0009	
46	Friction Factor Guess	=0.25*(LOG(B45/3.7+5.74/(B44^0.9)))^-2	0.0193	
47	Friction Factor	=0.25*(LOG(B45/3.7+2.51/(B44*B46^0.5)))^-2	0.0192	
48	Pressure Drop	=0.00000336*B47*B38*(B43^2)/B40/(B37^5)	8.185	psi
51				
52	ΔP Across Relief Valve Outlet			Units
53	Inner Pipe Diameter (conv.)	=B54/12	0.272	ft
54	> Inner Pipe Diameter	3.26	3.26	in
55	> Equivalent Length	51	51	ft
56	> gAr Density @ 2.0 bar & Temp.	10.55	10.55	mg/cc
57	gAr Density @ 2.0 bar (conv.)	=B56/1000*62.428	0.659	lbm/ft^3
58	> gAr Viscosity @ 2.0 bar & Temp.	0.0000798	0.0000798	g/cm-s
59	gAr Viscosity @ 2.0 bar (conv.)	=B58*100	0.00798	centipoise
60	Max. Mass Flow to Relief Valve	=B28	7900	lbm/hr
61	Reynolds Number	=6.31*B60/(B54*B59)	1920000	
62	> Relative Roughness (e/D)	0.00055	0.00055	
63	Friction Factor Guess	=0.25*(LOG(B62/3.7+5.74/(B61^0.9)))^-2	0.0174	
64	Friction Factor	=0.25*(LOG(B62/3.7+2.51/(B61*B63^0.5)))^-2	0.0173	
65	Pressure Drop	=0.00000336*B64*B55*(B60^2)/B57/(B54^5)	0.764	psi
66				

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Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
67	ΔP Across Rupture Disk Outlet			Units
68	Inner Pipe Diameter (conv.)	=B69/12	0.18	ft
69	> Inner Pipe Diameter	2.157	2.157	in
70	> Equivalent Length	1.75	1.75	ft
71	gAr Density @ 2.0 bar & Temp.	=B56	10.55	mg/cc
72	gAr Density @ 2.0 bar (conv.)	=B71/1000*62.428	0.659	lbm/ft^3
73	gAr Viscosity @ 2.0 bar & Temp.	=B58	0.0000798	g/cm-s
74	gAr Viscosity @ 2.0 bar (conv.)	=B73*100	0.00798	centipoise
75	Max. Mass Flow to Rupture Disk	=B43	8766	lbm/hr
76	Reynolds Number	=6.31*B75/(B69*B74)	3210000	
77	> Relative Roughness (e/D)	0.0009	0.0009	
78	Friction Factor Guess	=0.25*(LOG(B77/3.7+5.74/(B76^0.9)))^-2	0.0193	
79	Friction Factor	=0.25*(LOG(B77/3.7+2.51/(B76*B78^0.5)))^-2	0.0192	
80	Pressure Drop	=0.00000336*B79*B70*(B75^2)/B72/(B69^5)	0.283	psi
81				
82	Change in Gas at Common Outlet to Outside			Units
83	Pressure in Cryostat	=B4	19.75	psig
84	Pressure in Cryostat (conv.)	=(B83/14.696+1)*1.01325	2.375	bars
85	gAr Density @ 2.2 bars	=B9	11.77	mg/cc
86	gAr Density @ 2.4 bars	=B10	12.75	mg/cc
87	gAr Density @ 2.375 & Temp.	=(B84-2.2)/0.2*(B86-B85)+B85	12.627	mg/cc
88	Temp. at Common Outlet	=(B2*B17+84*B189)/(B17+B189)	94	K
89	> Pressure to Calculate Density	1.5	1.5	bars
90	*> gAr Density @ 1.5 bars & New Temp.	7.99	7.99	mg/cc
91	*> gAr Viscosity @ 1.5 bars & New Temp.	0.000078	0.000078	g/cm-s
92	gAr Viscosity @ 1.5 bar (conv.)	=B91*100	0.0078	centipoise
93				

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Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
94	ΔP Across Relief Valve			Units
95	> Critical Ratio (Pcr/P1) for Argon	0.487	0.487	
96	> Specific Heat Ratio (k) for Argon	=B168	1.75	
97	> Area of 2" x 3" Relief Valve	2.29	2.29	in^2
98	Flow Through Relief Valve	=B28	7900	lbm/hr
99	Flowing Temperature	=1.8*B2	173.	deg R
100	> Compressibility Factor	1	1	
101	> Nozzle Coefficient for type 93T	0.939	0.939	
102	Flowing Inlet Pressure (P1)	=B4+14.696-B33	32.45	psia
103	> Molecular Weight of Argon	39.948	39.95	g/mol
104	Critical Pressure (Pcr)	=B95*B102	15.8	psia
105	Outlet Pressure (P2) (using delta p's)	=14.696+B154+B133+B65	25.43	psia
106	Pressure Ratio (P2*/P1)	=(B102-0.55*((B102-B105)^0.98))/B102	0.885	
107	Theoretical Factor (F*) (using P2)	=SQRT((B96/(B96-1))*(B106^(2/B96)-B106^((B96+1)/B96)))	0.321	
108	Max. Theoretical Relief Flow (using F*)	=735*B97*B101*B102*B107*SQRT(B103/B99/B100)	7918	lbm/hr
109	Theoretical Percent of Relief Flow	=B108/B17	0.4751	
110	Pressure Drop Across Relief Valve	=B102-B105	7.026	psi
111				

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Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
112	ΔP Across Common Outlet to Cryocorner			Units
113	> Inner Pipe Diameter	0.355	0.355	ft
114	Inner Pipe Diameter (conv.)	=B113*12	4.26	in
115	> Equivalent Length	238	238	ft
116	gAr Density @ 1.5 bar & New Temp.	=B90	7.99	mg/cc
117	gAr Density @ 1.5 bar (conv.)	=B116/1000*62.428	0.499	lbm/ft^3
118	*> gN2 Gas Density @ 1.5 bar & New Temp.	5.653	5.653	mg/cc
119	gN2 Gas Density @ 1.5 bar (conv.)	=B118/1000*62.428	0.353	lbm/ft^3
120	Gas Mixture Density @1.5 bar	=(B17*B117+B127*B119)/B128	0.474	lbm/ft^3
121	gAr Viscosity @ 1.5 bar & New Temp.	=B91	0.000078	g/cm-s
122	gAr Viscosity @ 1.5 bar (conv.)	=B121*100	0.0078	centipoise
123	*> gN2 Viscosity @ 1.5 bar & New Temp.	0.0000643	0.0000643	g/cm-s
124	gN2 Viscosity @ 1.5 bar (conv.)	=B123*100	0.00643	centipoise
125	Mixture Viscosity @1.5 bar	=(B17*B122+B127*B124)/B128	0.007563	centipoise
126	Max. Mass Flow of Argon Gas	=B17	16666	lbm/hr
127	Max. Flow of Nitrogen Gas	=B189	3477	lbm/hr
128	Mass Flow of Mixture	=B126+B127	20143	lbm/hr
129	Reynolds Number	=6.31*B128/(B114*B125)	3940000	
130	> Relative Roughness (e/D)	0.0004	0.0004	
131	Friction Factor Guess	=0.25*(LOG(B130/3.7+5.74/(B129^0.9)))^-2	0.0161	
132	Friction Factor	=0.25*(LOG(B130/3.7+2.51/(B129*B131^0.5)))^-2	0.0161	
133	Pressure Drop	=0.00000336*B132*B115*(B128^2)/B120/(B114^5)	7.838	psi
134				

Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
135	ΔP from Cryocorner to Outside			Units
136	> Inner Pipe Diameter	0.53	0.53	ft
137	Inner Pipe Diameter (conv.)	=B136*12	6.36	in
138	> Equivalent Length	516	516	ft
139	gAr Gas Density @ 1.5 bar & New Temp.	=B90	7.99	mg/cc
140	gAr Gas Density @ 1.5 bar (conv.)	=B139/1000*62.428	0.499	lbm/ft^3
141	gN2 Gas Density @ 1.5 bar & New Temp.	=B118	5.653	mg/cc
142	gN2 Gas Density @ 1.5 bar (conv.)	=B141/1000*62.428	0.353	lbm/ft^3
143	Gas Mixture Density @1.5 bar	=(B17*B140+B189*B142)/B149	0.474	lbm/ft^3
144	gAr Viscosity @ 1.5 bar & New Temp.	=B121	0.000078	g/cm-s
145	gAr Viscosity @ 1.5 bar (conv.)	=B144*100	0.0078	centipoise
146	gN2 Viscosity @ 1.5 bar & New Temp.	=B123	0.0000643	g/cm-s
147	gN2 Viscosity @ 1.5 bar (conv.)	=B146*100	0.00643	centipoise
148	Gas Mixture Viscosity @1.5 bar	=(B17*B145+B189*B147)/B149	0.007563	centipoise
149	Max. Mass Flow of Gas Mixture	=B128	20143	lbm/hr
150	Reynolds Number	=6.31*B149/(B137*B148)	2640000	
151	> Relative Roughness (e/D)	0.00027	0.00027	
152	Friction Factor Guess	=0.25*(LOG(B151/3.7+5.74/(B150^0.9)))^-2	0.015	
153	Friction Factor	=0.25*(LOG(B151/3.7+2.51/(B150*B152^0.5)))^-2	0.0149	
154	Pressure Drop	=0.00000336*B153*B138*(B149^2)/B143/(B137^5)	2.13	psi
155				
156	Summation of Equivalent ΔPs			Units
157	Relief Valve Inlet Pressure Drop	=B33	1.993	psi
158	Relief Valve Outlet Pressure Drop	=B65	0.764	psi
159	Relief Valve Pressure Drop	=B110	7.026	psi
160	Relief Valve/Disk Branch	=B33+B65+B110	9.782	psi
161	Rupture Disk Inlet Pressure Drop	=B48	8.185	psi
162	Rupture Disk Outlet Pressure Drop	=B80	0.283	psi
163	Rupture Disk Pressure Drop	=B157+B158+B159-B161-B162	1.313	psi
164	Common Outlet Pressure Drop	=B133	7.838	psi
165	Cryocorner to Outside Pressure Drop	=B154	2.13	psi
166				

Maximum ECS Relief Flow Calculation 10/18/91

	A	B	C	D
167	ΔP Across Rupture Disk			Units
168	>Argon Specific Heat Ratio (k)	1.745	1.745	
169	Critical Ratio	=(2/(B168+1))^(B168/(B168-1))	0.476	
170	> Area of 3" Rupture Disk	=3.14159*(3^2)/4	7.069	in^2
171	Flow Through Rupture Disk	=B43	8766	lbm/hr
172	Flowing Temperature	=1.8*B2	173	deg R
173	> ASME Coefficient (K)	0.62	0.62	
174	Pressure Ratio (Pe/Po)	=B179/B176	0.95	
175	gAr Flow Constant for Subsonic Flow(C1)	=SQRT(2*32.2/1545*(B168/(B168-1))*(B174^(2/B168)-B17	0.045	
176	Flowing Inlet Pressure (Po)	=B4+14.696-B48	26.26	psia
177	> Molecular Weight of Argon	39.948	39.948	g/mol
178	Critical Pressure (Pcr)	=B169*B176	12.51	psia
179	Outlet Pressure (Pe) (using delta p's)	=14.696+B154+B133+B80	24.95	psia
180	Pressure Drop Across Rupture Disk	=B176-B179	1.313	psi
181	Maximum Theoretical Rupture Disk Flow	=B170*B173*B175*B176*SQRT(B177/B172)*60*60	8897	lbm/hr
182	Actual Rupture Disk Flow	=B43	8766	lbm/hr
183				
184	Maximum Flow from Condensers			units
185	> Max. Flow of Liquid Nitrogen	9.3	9.3	gpm
186	Max. Flow of Liquid Nitrogen (conv.)	=B185/7.48	1.24	ft^3/min
187	Density of LN2 @ 3.5 atm	0.747	0.747	g/cc
188	Density of LN2 (conv.)	=B187*62.4	46.6128	lbm/ft^3
189	Mass Flow of LN2	=B186*B188*60	3477	lbm/hr
190				
191	**Notes:**			
192	*> indicates that this value must be changed for a			
193	new flowrate			
194				
195	> indicates variable not requiring change for new			
196	flowrates			
197				
198	(conv.) indicates the previous value converted to new			
199	units			

As with the ECN, the total mass flow for the ECS can be calculated from line 108 for the maximum relief valve flow, and line 181 for the maximum rupture disk flow:

$$\rho\left(q_{rel}^{ECS}\right)_{max} = 7918\,\frac{lb_m}{hr}\,(\text{relief valve}) + 8897\,\frac{lb_m}{hr}\,(\text{rupture disk}) = 16{,}815\,\frac{lb_m}{hr}$$

Now the ECN and ECS relief piping flowrates can be compared:

$$\frac{q_{rel}^{ECS}}{q_{rel}^{ECN}} = \frac{\rho q_{rel}^{ECS}}{\rho q_{rel}^{ECN}} = \frac{16{,}815\,\frac{lb_m}{hr}}{15{,}198\,\frac{lb_m}{hr}} = 1.106$$

The maximum relief outlet flow from the ECS is greater than the maximum relief outlet flow from the ECN by about 10%.

Conclusion

Since the flowrate <u>out</u> of the ECS relative to the flowrate <u>out</u> of the ECN (1.106 times ECN) is greater than the flowrate <u>into</u> the ECS relative to the flowrate <u>into</u> the ECN (1.054 times ECN), the ECN is the flowrate limiting vessel.

Relief Valve Capacity for Filling ECN at Maximum Operating Temperature

Although the maximum temperature calculated by this engineering note is 290 K, the spreadsheet requires flow through both the relief valve and the rupture disk. Although this situation satifies safety conditions regarding the overpressurization of the vessel, in reality, the operating procedures should limit the temperature to a much lower value, to prevent the rupture disk from bursting. This section calculates the temperature at which the maximum flow from the argon dewar requires only the relief valve, and not the rupture disk.

The procedure is the same as before, so the same spreadsheet is used. The only difference is that in the section, "Conversion of Liquid to Gas at Module Temp.", line 18 is not guessed through iteration, but is set initially to 100%. This forces all of the flow through the relief valve, and all of the sections related to the rupture disk, including the pressure drops before and after the rupture disk, are essentially excluded from the calculation. Rather than physically remove these sections, they remain in the spreadsheet, but have no effect on the temperature. The bulk temperature is guessed as before, and iterations proceed, changing the various gas properties of argon and nitrogen each time, until a suitable temperature is found. The conclusion was that with a maximum flow of 12.3 gpm, as calculated previously, the maximum module temperature at which only the relief valve is required is at least 110 K. Note that the theoretical percent of relief flow (line 109) is greater than 100%, indicating that the relief capacity is above the inlet flow. This can be verified by comparing line 98 (actual flow) and line 108 (maximum theoretical flow).

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
1	Conversion of Liquid to Gas at Module Temp.			Units
2	*> Bulk Temp. of Modules	110	110	K
3	> Max. Flow of Liquid Argon to Cryostat	12.3	12.3	gpm
4	> Pressure in Cryostat	19.75	19.75	psig
5	Pressure in Cryostat (conv.)	=(B4/14.696+1)*1.01325	2.375	bars
6	> lAr Density @ 2.2 bars	1.342421	1.34	g/cc
7	> lAr Density @ 2.4 bars	1.335861	1.34	g/cc
8	lAr Density @ 2.375 bars	=(B5-2.2)/0.2*(B7-B6)+B6	1.337	g/cc
9	*> gAr Density @ 2.2 bars	9.979	9.979	mg/cc
10	*> gAr Density @ 2.4 bars	10.922	10.922	mg/cc
11	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	10.804	mg/cc
12	gAr Density @ 2.375 bars (conv.)	=B11/1000*62.428	0.674	lbm/ft^3
13	Maximum Flow of Argon Gas	=B3*B8/B11*1000	1522	gpm
14	Maximum Flow of Argon Gas (conv.)	=B13*0.13368	203	cfm
15	Air Equivalent Flow @STP	=6.32*B17*356/B16*SQRT(B99/(520*B177*28.97))	881	scfm air
16	Specific Heat Constant, C, for Ar	=520*SQRT(B168*(2/(B168+1))^((B168+1)/(B168-1)))	381	
17	Max. Mass Flow of Argon Gas	=B14*B12*60	8232	lbm/hr
18	*> Percent of Mass Flow to Relief Valve	1	1	
19				
20	ΔP Across Relief Valve Inlet			Units
21	> Inner Pipe Diameter	0.206	0.206	ft
22	Inner Pipe Diameter (conv.)	=B21*12	2.472	in
23	> Equivalent Length	38	38	ft
24	Ar Gas Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	10.804	mg/cc
25	Ar Gas Density @ 2.375 bars (conv.)	=B24/1000*62.428	0.674	lbm/ft^3
26	*> gAr Viscosity @ 2.4 bars & Temp.	0.0000909	0.0000909	g/cm-s
27	gAr Viscosity @ 2.4 bars (conv.)	=B26*100	0.00909	centipoise
28	Max. Mass Flow to Relief Valve	=B17*B18	8232	lbm/hr
29	Reynolds Number	=6.31*B28/(B22*B27)	2310000	
30	> Relative Roughness (e/D)	0.0007	0.0007	
31	Friction Factor Guess	=0.25*(LOG(B30/3.7+5.74/(B29^0.9)))^-2	0.0183	
32	Friction Factor	=0.25*(LOG(B30/3.7+2.51/(B29*B31^0.5)))^-2	0.0182	
33	Pressure Drop	=0.00000336*B32*B23*(B28^2)/B25/(B22^5)	2.531	psi
34				

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
35	ΔP Across Rupture Disk Inlet			Units
36	Inner Pipe Diameter (conv.)	=B37/12	0.172	f t
37	> Inner Pipe Diameter	2.067	2.067	in
38	> Equivalent Length	49	49	f t
39	gAr Density @ 2.375 & Temp.	=(B5-2.2)/0.2*(B10-B9)+B9	10.804	mg/cc
40	gAr Density @ 2.375 bars (conv.)	=B39/1000*62.428	0.674	lbm/ft^3
41	gAr Viscosity @ 2.4 bars	=B26	0.0000909	g/cm-s
42	gAr Viscosity @ 2.4 bars (conv.)	=B41*100	0.00909	centipoise
43	Max. Mass Flow to Rupture Disk	=B17*(1-B18)	0	lbm/hr
44	Reynolds Number	=6.31*B43/(B37*B42)	0	
45	> Relative Roughness (e/D)	0.0009	0.0009	
46	Friction Factor Guess	0	0	
47	Friction Factor	0	0	
48	Pressure Drop	0	0	psi
51				
52	ΔP Across Relief Valve Outlet			Units
53	Inner Pipe Diameter (conv.)	=B54/12	0.272	f t
54	> Inner Pipe Diameter	3.26	3.26	in
55	> Equivalent Length	51	51	f t
56	*> gAr Density @ 2.0 bar & Temp.	9.04	9.04	mg/cc
57	gAr Density @ 2.0 bar (conv.)	=B56/1000*62.428	0.564	lbm/ft^3
58	*> gAr Viscosity @ 2.0 bar & Temp.	0.0000907	0.0000907	g/cm-s
59	gAr Viscosity @ 2.0 bar (conv.)	=B58*100	0.00907	centipoise
60	Max. Mass Flow to Relief Valve	=B28	8232	lbm/hr
61	Reynolds Number	=6.31*B60/(B54*B59)	1760000	
62	> Relative Roughness (e/D)	0.00055	0.00055	
63	Friction Factor Guess	=0.25*(LOG(B62/3.7+5.74/(B61^0.9)))^-2	0.0174	
64	Friction Factor	=0.25*(LOG(B62/3.7+2.51/(B61*B63^0.5)))^-2	0.0173	
65	Pressure Drop	=0.00000336*B64*B55*(B60^2)/B57/(B54^5)	0.969	psi
66				

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
67	ΔP Across Rupture Disk Outlet			Units
68	Inner Pipe Diameter (conv.)	=B69/12	0.18	ft
69	> Inner Pipe Diameter	2.157	2.157	in
70	> Equivalent Length	1.75	1.75	ft
71	gAr Density @ 2.0 bar & Temp.	=B56	9.04	mg/cc
72	gAr Density @ 2.0 bar (conv.)	=B71/1000*62.428	0.564	lbm/ft^3
73	gAr Viscosity @ 2.0 bar & Temp.	=B58	0.0000907	g/cm-s
74	gAr Viscosity @ 2.0 bar (conv.)	=B73*100	0.00907	centipoise
75	Max. Mass Flow to Rupture Disk	=B43	0	lbm/hr
76	Reynolds Number	=6.31*B75/(B69*B74)	0	
77	> Relative Roughness (e/D)	0.0009	0.0009	
78	Friction Factor Guess	0	0	
79	Friction Factor	0	0	
80	Pressure Drop	0	0	psi
81				
82	Change in Gas at Common Outlet to Outside			Units
83	Pressure in Cryostat	=B4	19.75	psig
84	Pressure in Cryostat (conv.)	=(B83/14.696+1)*1.01325	2.375	bars
85	gAr Density @ 2.2 bars	=B9	9.979	mg/cc
86	gAr Density @ 2.4 bars	=B10	10.922	mg/cc
87	gAr Density @ 2.375 & Temp.	=(B84-2.2)/0.2*(B86-B85)+B85	10.804	mg/cc
88	Temp. at Common Outlet	=(B2*B17+84*B189)/(B17+B189)	100	K
89	> Pressure to Calculate Density	1.5	1.5	bars
90	*> gAr Density @ 1.5 bars & New Temp.	7.458	7.458	mg/cc
91	*> gAr Viscosity @ 1.5 bars & New Temp.	0.0000826	0.0000826	g/cm-s
92	gAr Viscosity @ 1.5 bar (conv.)	=B91*100	0.00826	centipoise
93				

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
94	ΔP Across Relief Valve			Units
95	> Critical Ratio (Pcr/P1) for Argon	0.487	0.487	
96	> Specific Heat Ratio (k) for Argon	=B168	1.72	
97	> Area of 2" x 3" Relief Valve	2.29	2.29	in^2
98	Flow Through Relief Valve	=B28	8232	lbm/hr
99	Flowing Temperature	=1.8*B2	198	deg R
100	> Compressibility Factor	1	1	
101	> Nozzle Coefficient for type 93T	0.939	0.939	
102	Flowing Inlet Pressure (P1)	=B4+14.696-B33	31.91	psia
103	> Molecular Weight of Argon	39.948	39.95	g/mol
104	Critical Pressure (Pcr)	=B95*B102	15.54	psia
105	Outlet Pressure (P2) (using delta p's)	=14.696+B154+B133+B65	21.22	psia
106	Pressure Ratio (P2*/P1)	=(B102-0.55*((B102-B105)^0.98))/B102	0.824	
107	Theoretical Factor (F*) (using P2)	=SQRT((B96/(B96-1))*(B106^(2/B96)-B106^((B96+1)/B96)))	0.385	
108	Max. Theoretical Relief Flow (using F*)	=735*B97*B101*B102*B107*SQRT(B103/B99/B100)	8723	lbm/hr
109	Theoretical Percent of Relief Flow	=B108/B17	1.0596	
110	Pressure Drop Across Relief Valve	=B102-B105	10.69	psi
111				

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
112	ΔP Across Common Outlet to Platform Bayonet			Units
113	> Inner Pipe Diameter	0.355	0.355	f t
114	Inner Pipe Diameter (conv.)	=B113*12	4.26	in
115	> Equivalent Length	273	273	f t
116	gAr Density @ 1.5 bar & New Temp.	=B90	7.458	mg/cc
117	gAr Density @ 1.5 bar (conv.)	=B116/1000*62.428	0.466	lbm/ft^3
118	*> gN2 Gas Density @ 1.5 bar & New Temp.	4.76381	4.764	mg/cc
119	gN2 Gas Density @ 1.5 bar (conv.)	=B118/1000*62.428	0.297	lbm/ft^3
120	Gas Mixture Density @1.5 bar	=(B17*B117+B127*B119)/B128	0.403	lbm/ft^3
121	gAr Viscosity @ 1.5 bar & New Temp.	=B91	0.0000826	g/cm-s
122	gAr Viscosity @ 1.5 bar (conv.)	=B121*100	0.00826	centipoise
123	*> gN2 Viscosity @ 1.5 bar & New Temp.	0.00007488	0.00007488	g/cm-s
124	gN2 Viscosity @ 1.5 bar (conv.)	=B123*100	0.007488	centipoise
125	Mixture Viscosity @1.5 bar	=(B17*B122+B127*B124)/B128	0.007973	centipoise
126	Max. Mass Flow of Argon Gas	=B17	8232	lbm/hr
127	Max. Flow of Nitrogen Gas	=B189	4861	lbm/hr
128	Mass Flow of Mixture	=B126+B127	13093	lbm/hr
129	Reynolds Number	=6.31*B128/(B114*B125)	2430000	
130	> Relative Roughness (e/D)	0.0004	0.0004	
131	Friction Factor Guess	=0.25*(LOG(B130/3.7+5.74/(B129^0.9)))^-2	0.0162	
132	Friction Factor	=0.25*(LOG(B130/3.7+2.51/(B129*B131^0.5)))^-2	0.0161	
133	Pressure Drop	=0.00000336*B132*B115*(B128^2)/B120/(B114^5)	4.489	psi
134				

Maximum Module Temperature - Lar Dewar to ECN - Relief Valve Only 10/18/91

	A	B	C	D
135	ΔP from Platform Bayonet to Outside			Units
136	> Inner Pipe Diameter	0.53	0.53	ft
137	Inner Pipe Diameter (conv.)	=B136*12	6.36	in
138	> Equivalent Length	516	516	ft
139	gAr Gas Density @ 1.5 bar & New Temp.	=B90	7.458	mg/cc
140	gAr Gas Density @ 1.5 bar (conv.)	=B139/1000*62.428	0.466	lbm/ft^3
141	gN2 Gas Density @ 1.5 bar & New Temp.	=B118	4.764	mg/cc
142	gN2 Gas Density @ 1.5 bar (conv.)	=B141/1000*62.428	0.297	lbm/ft^3
143	Gas Mixture Density @1.5 bar	=(B17*B140+B189*B142)/B149	0.403	lbm/ft^3
144	gAr Viscosity @ 1.5 bar & New Temp.	=B121	0.0000826	g/cm-s
145	gAr Viscosity @ 1.5 bar (conv.)	=B144*100	0.00826	centipoise
146	gN2 Viscosity @ 1.5 bar & New Temp.	=B123	0.00007488	g/cm-s
147	gN2 Viscosity @ 1.5 bar (conv.)	=B146*100	0.007488	centipoise
148	Gas Mixture Viscosity @1.5 bar	=(B17*B145+B189*B147)/B149	0.007973	centipoise
149	Max. Mass Flow of Gas Mixture	=B128	13093	lbm/hr
150	Reynolds Number	=6.31*B149/(B137*B148)	1630000	
151	> Relative Roughness (e/D)	0.00027	0.00027	
152	Friction Factor Guess	=0.25*(LOG(B151/3.7+5.74/(B150^0.9)))^-2	0.0152	
153	Friction Factor	=0.25*(LOG(B151/3.7+2.51/(B150*B152^0.5)))^-2	0.0151	
154	Pressure Drop	=0.00000336*B153*B138*(B149^2)/B143/(B137^5)	1.07	psi
155				
156	Summation of Equivalent ΔPs			Units
157	Relief Valve Inlet Pressure Drop	=B33	2.531	psi
158	Relief Valve Outlet Pressure Drop	=B65	0.969	psi
159	Relief Valve Pressure Drop	=19.75-B157-(B165+B164+B158)	10.69	psi
160	Relief Valve/Disk Branch	=B33+B65+B110	14.19	psi
161	Rupture Disk Inlet Pressure Drop	=B48	0	psi
162	Rupture Disk Outlet Pressure Drop	=B80	0	psi
163	Rupture Disk Pressure Drop	0	0	psi
164	Common Outlet Pressure Drop	=B133	4.489	psi
165	Platform to Outside Pressure Drop	=B154	1.07	psi
166				

	A	B	C	D
167	ΔP Across Rupture Disk			Units
168	*>Argon Specific Heat Ratio (k)	1.7186	1.7186	
169	Critical Ratio	=(2/(B168+1))^(B168/(B168-1))	0.48	
170	> Area of 3" Rupture Disk	=3.14159*(3^2)/4	7.069	in^2
171	Flow Through Rupture Disk	=B43	0	lbm/hr
172	Flowing Temperature	=1.8*B2	198	deg R
173	> ASME Coefficient (K)	0.62	0.62	
174	Pressure Ratio (Pe/Po)	=B179/B176	0.588	
175	gAr Flow Constant for Subsonic Flow(C1)	=SQRT(2*32.2/1545*(B168/(B168-1))*(B174^(2/B168)-B174	0.103	
176	Flowing Inlet Pressure (Po)	=B4+14.696-B48	34.45	psia
177	> Molecular Weight of Argon	39.948	39.948	g/mol
178	Critical Pressure (Pcr)	=B169*B176	16.53	psia
179	Outlet Pressure (Pe) (using delta p's)	=14.696+B154+B133+B80	20.26	psia
180	Pressure Drop Across Rupture Disk	0	0	psi
181	Maximum Theoretical Rupture Disk Flow	=B170*B173*B175*B176*SQRT(B177/B172)*60*60	25250	lbm/hr
182	Actual Rupture Disk Flow	=B43	0	lbm/hr
183				
184	Maximum Flow from Condensers			units
185	> Max. Flow of Liquid Nitrogen	13	13	gpm
186	Max. Flow of Liquid Nitrogen (conv.)	=B185/7.48	1.74	ft^3/min
187	Density of LN2 @ 3.5 atm	0.747	0.747	g/cc
188	Density of LN2 (conv.)	=B187*62.4	46.6128	lbm/ft^3
189	Mass Flow of LN2	=B186*B188*60	4861	lbm/hr