ECN Pressure and Vacuum Vessel Engineering Notes

3740.224-EN-323

K. Dixon/J. Wu
October 17, 1991

Checked by

_____

Prepared by: Kelly Dixon, RD/DP
Preparation date: 25 Oct 91

Fill in the label information below:

This vessel conforms to engineering standard SD37

Vessel Title North Endcap Calorimeter (NEC) Cryostat

Vessel Number RD 4025

Vessel Drawing Number 3740.224-ME-273065

Maximum Allowable
Working Pressure (MAWP) 15 + F.V. (Full Vacuum) PSI

Working Temperature Range -298 °F +100 °F

Contents Liquid argon, calorimeter modules, instrumentation

Designer/Manufacturer Process Engineering Inc.

Test Pressure (if tested at Fermi)	Acceptance
40 PSI, Hydraulic	Date: 25 June 91
	Pneumatic X

Accepted as conforming to standard by

of Division/Section *Research Division* *25 Oct 91*

NOTE: Any subsequent changes in contents, pressures, temperatures, valving, etc., which affect the safety of this vessel shall require another review and test.

Actual signature
required in this
space

Reviewed by: by C. J. Kevlache Date: 10-24-91

Director's signature (or designee) if the vessel is for manned areas but doesn't conform to the requirements of the standard.

Date:

Lab Property Number(s): _____

Lab Location Code: DAB (obtain from Safety Officer)

Purpose of Vessel(s): Liquid argon calorimeter for DØ Colliding Detector

Vessel Capacity/Size: 1200 ft³ w/o modules Diameter: 192 1/4" Length: 95"

Normal Operating Pressure (OP) 5 PSI

MAWP-OP = 10 PSI

Is the above enough to provide relief cracking pressure tolerance plus system uncertainty tolerance per M-9. *Yes*

As an option, provide a photo of the entire vessel in the Appendix.

5031TA-5

List the numbers of all pertinent drawings and the location of the originals.
(Append copies).

<u>Drawing #</u>	<u>Location of Original</u>
3740.224-ME-273065	Dø files, DAB
3740.220-ME-222256	" " "
3740. -ME-222394, sheet 2	" " "
3740.224-ME-273030	" " "

2 Design Verification

Does the vessel(s) have a U stamp? Yes ☒ No ☐ . If "Yes", fill out data below and skip page 3; if "No", fill out page 3 and skip this page.

Staple photo of U stamp plate below.

Copy "U" label details to the side if photo is not clear of if copies are unreadable.

Copy data here:

On the sketch below, circle all applicable sections of the ASME code per Section VIII, Division I. List the results of all calculations. (Insert copies of calculations in the appendix).

Summary of ASME Code & Related Design References

<u>Item</u>	<u>DØ EN #</u>
Design Summary - EC Cryostats	3740.224-EN-194
EC Contract including design spec. & Battelle review	3740.224-EN-325
ASME Code Data Report	3740.224-EN-326
Structural Evaluation of the EC Cryostat Stanchions	3740.224-EN-216

If this vessel is exceptional or had exceptional parts, list their details under 5.6. Yes _____ No _____

3 System Venting. Provide the system schematic in the Appendix, if the vessel safety is system sensitive.

Is it possible to isolate the relief valves by a valve from the vessel?

Yes _____ No X*

If "Yes", the system must conform to M-5. Provide an explanation on the appended schematic. (An isolatable vessel, not conforming to M-5 violates the Standard.)

Is the relief cracking pressure set at or below the M.A.W.P.?

Yes X No _____ Actual setting 13 PSI
(A no response violates the Standard.)

Is the pressure drop of the relief system at maximum anticipated flow such that vessel pressure never rises above the following? (UG 125)

Yes X No _____
110% of MAWP (one relief)
116% of MAWP (multiple reliefs)
121% of MAWP (unexpected heat source)

Provide test or calculational proof in the Appendix.
(Non-conforming pressure rises violate the Standard.)

List of reliefs and settings:

<u>Manufacturer</u>	<u>Relief</u>	<u>Setting</u>	<u>Flow Rate</u> **	<u>Size</u>
<u>AGCO</u>	<u>relief valve, Model 9ST***</u>	<u>13 psig</u>	<u>760 scfm air</u>	<u>2" x 3"</u>
<u>Fike Metal Products</u>	<u>double rupture disk ass'y, CPV Series</u>	<u>18 psig (vessel) 10 psig (manifold)</u>	<u>850 scfm air</u>	<u>3"</u>
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____

Is the relief device an ASME stamped device? Yes _____ No X

4 Operating Procedure

Is an operating procedure necessary for the safe operation of this vessel?

Yes X No _____. If "Yes", please append.

5 Welding Information

Has the vessel been fabricated in a Fermilab shop? Yes _____ No X

If "Yes", append a copy of the welding shop statement of welder qualification and a copy of the Welding Procedure Specification (WPS) used to weld this vessel.

6 Exceptional, Existing, Used, and Non-Manned Area Vessels

Is this vessel or any part thereof in the above categories? Yes _____ No X

If "Yes", follow the Engineering Note requirements for documentation in free form below.

* Block Valve is on the DISCHARGE side of the relief valve. See EN-155 for further information.

** Evaluated at 96K inlet temperature. Flow rates are down rated for system effects
(upstream and downstream pressure drops).

*** Pilot operated type; sense line from rupture disk inlet.

EXHIBIT B
Pressure Testing Permit*

Date: 25 June 91

Type of Test: ☐ Hydrostatic ☒ Pneumatic

Test Pressure: 40 psig Maximum Allowable Working Pressure: 15+FW psig

Items to be Tested: ECN crystal w/ electrical feedthrough boxes attached to the top of the vessel.

Location of Test: North Sidewalk / DAB Date and Time: 7/17/91, 5 PM

Hazards Involved: Large built up forces due to pressures over large surface areas, possible head separation, shrapnel, etc. Cryogen used to pressurize vessel.

Safety Precautions Taken: W. high bay area evacuated aside from test personnel in pit protected by concrete wall. Relief valves on piping.

Special Conditions or Requirements: Use remote camera to monitor pressure. The vacuum heads will not be attached at this time.

Test Coordinator: Kelly D'Amico Dept/Date: RP/DD 25 June 91

Division/Section Safety Officer: Barbi Dept/Date: RD/ES/H 25 June 91

Division/Section Head: Chen Dept/Date: RDO June 26, 91

Results: Less than 1/4 psi drop in 30 minutes of 30 psig starting pressure.

Witness: Authorized Code Inspector
RO/ES/H Martha Michaels
(Safety Officer or Designee)

Dept/Date: 07-17-91
17 July 91

*Must be signed by division/section safety officer and division head prior to conducting test. It is the responsibility of the test coordinator to obtain signatures

Pressure Relief Appendices

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Vacuum Vessel Engineering Note.....	appended

Pressure Relief Calculation Summary

<i>Condition</i>	<i>Req'd Flow Capacity (scfm air)</i>
1. Fire	450 (ref. EN-6)
2. Insulating Vacuum Loss	29 (ref. EN-6)
3. Condenser Coil Rupture	443 (ref. EN-263)
4. Filling While Modules are Warm	1572 @155 K*

The total relief capacity for both rupture disk and relief valve evaluated at 96K with 3477 lb/hr saturated GN2 flowing simultaneously through the vent piping is **1604 scfm air**.

* The worst case situation is when the CC vessel is full and accidentally discharges LAr through the fill/drain line into a warm ECN. This flowrate matches the relief system capacity at a relief device inlet temperature of 155 K, both protective equipment and procedures will ensure that no attempt will be made to fill the cryostat above this temperature.

Summary of Argon Sources Investigated

Source	Source Relief Pressure (psig)	maximum driving pressure (psi)	maximum flowrate (gpm)	maximum module temp. (K)
LAr Dewar	20	3.21	12.3	290
CC cryostat	13	3.11	18.4	155
any	-	-	24.1	96

Note: All values based on flow through both relief valve and rupture disk.

K. Dixon
2 Aug 91

Simplified Cryostat Venting Arrangement

Determine ECN Relieving Flow at Steady State Operating Conditions

The following calculations arranged in a spreadsheet format derive the flowrate from both ECN relieving devices. In this case it is assumed that the ECN is full of liquid argon and it is in its steady state cooling mode. One of the other cryostats is assumed to be cooling down while the other is being filled with LAr.

Other assumptions in this analysis include:

1. Pressure in the cryostat is 19.75 psig ($1.16 \times (\text{MAWP} + \text{FV})$).
2. Gaseous Nitrogen is concurrently flowing in the vent piping at a rate of 3477 lb/hr. This is derived from 0.3 gpm required for ECN steady state conditions, 4 gpm required for cooldown (max.), and 5 gpm required for filling with LAr (max.)
3. Mixture mass flows are at their maximum at the junction of the relief device outlets on the ECN (GN2 mass flow actually increases gradually at junctions toward the ECS and there is a short segment of piping between the GAr outlets and the condenser exhaust).
4. The temperature in the vent piping is negligible since a large majority of this piping is insulated.
5. All flows are treated as incompressible (max. Mach No. < 0.3).
6. The temperature of the GN2 prior to mixing in the vent manifold is 84 K, saturated property at 2 atm.
7. Flow equations apply to weight-averaged mixture densities and viscosities.

For further information on the formulas used and the rationale for the calculations performed in each section, refer to EN-321, "Cryostat Filling Limitations for Proposed Ar Dewar Pressure Increase".

Explanation of Methodology

The basic purpose of the spreadsheet was to provide a complete model so that the maximum flow of argon to the reliefs (line 3) could be determined. The bulk temperature of the modules (line 2) was set at 96 K, the saturation temperature of argon at the cryostat pressure of 19.75 psig. A number was then picked as a guess for the maximum argon flow (line 3). Then a number was picked as a guess for the percent of mass flow to the relief valve (line 18). From these two numbers, the actual flow through the relief valve (line 98) could be determined. 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 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 through 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 total flow rate was lowered. Using the new total flow, the first set of iterations was repeated to match the percent of flow to the relief valve, and the rupture disk flow was compared again. The total flow 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. 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.

Conclusions

The total mass flow capacity of argon through the reliefs at saturated conditions is given on line 13 and the air equivalent flow @STP is printed on line 15. The percentage of these flows going through the relief valve is shown on line 18. This relief valve flow is calculated to be 760 scfm air; this value is much higher than the usual failure scenarios given in the summary page.

A summation of the pressure drops appears on lines 156 through 165. Since the pilot senses pressure near the rupture disk inlet, there was concern that the inlet pressure drop to the rupture disk (line 161) might be large enough that the pressure being sensed would drop below the relief valve's reset pressure, closing the relief valve. An investigation into this possibility concluded that it could be avoided by increasing the blowdown of the relief valve to its maximum of 18% of the set pressure. Taking into account a maximum error of 3% (ref. Anderson Greenwood), the worst case blowdown would be $(18\% - 3\%) \times (13 \text{ psi set pressure}) = 1.95 \text{ psi}$, which results in a margin of about 1 psi between the relief valve reset pressure ($13 \text{ psig} - 1.95 \text{ psi} = 11.05 \text{ psig} = 25.746 \text{ psia}$) and the lowest pressure at the rupture disk inlet (26.719 psia based on the spreadsheet pressure drops). This margin was accepted by the safety committee, and the relief valve blowdowns on all three cryostats are set at the maximum.

Maximum ECN Relief Flow Calculation 10/10/91

	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	24.1	24.1	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	$=B3*B8/B11*1000$	2551	gpm
14	Maximum Flow of Argon Gas (conv.)	$=B13*0.13368$	341	cfm
15	Air Equivalent Flow @STP	$=6.32*B17*356/B16*SQRT(B99/(520*B177*28.97))$	1604	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	$=B14*B12*60$	16130	lbm/hr
18	*> Percent of Mass Flow to Relief Valve	0.472	0.472	
19				
20	ΔP Across Relief Valve Inlet			Units
21	> Inner Pipe Diameter	0.206	0.206	f t
22	Inner Pipe Diameter (conv.)	$=B21*12$	2.472	in
23	> Equivalent Length	38	38	f t
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	$=B17*B18$	7614	lbm/hr
29	Reynolds Number	$=6.31*B28/(B22*B27)$	2420000	
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	$=0.00000336*B32*B23*(B28^2)/B25/(B22^5)$	1.852	psi
34				

Maximum ECN Relief Flow Calculation 10/10/91

	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	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)	8517	lbm/hr
44	Reynolds Number	=6.31*B43/(B37*B42)	3240000	
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)	7.728	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.	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	7614	lbm/hr
61	Reynolds Number	=6.31*B60/(B54*B59)	1850000	
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)	0.71	psi
66				

Maximum ECN Relief Flow Calculation 10/10/91

	A	B	C	D
67	ΔP Across Rupture Disk Outlet			Units
68	Inner Pipe Diameter (conv.)	=B69/12	0.18	f t
69	> Inner Pipe Diameter	2.157	2.157	in
70	> Equivalent Length	1.75	1.75	f t
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	8517	lbm/hr
76	Reynolds Number	=6.31*B75/(B69*B74)	3120000	
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	0.0193	
80	Pressure Drop	=0.00000336*B79*B70*(B75^2)/B72/(B69^5)	0.267	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				

Maximum ECN Relief Flow Calculation   10/10/91

	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	7614	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	32.59	psia
103	> Molecular Weight of Argon	39.948	39.95	g/mol
104	Critical Pressure (Pcr)	=B95*B102	15.87	psia
105	Outlet Pressure (P2) (using delta p's)	=14.696+B154+B133+B65	25.96	psia
106	Pressure Ratio (P2*/P1)	=(B102-0.55*((B102-B105)^0.98))/B102	0.892	
107	Theoretical Factor (F*) (using P2)	=SQRT(((B96/(B96-1))^(B106^(2/B96)-B106^((B96+1)/B96))))	0.313	
108	Max. Theoretical Relief Flow (using F*)	=735*B97*B101*B102*B107*SQRT(B103/B99/B100)	7740	lbm/hr
109	Theoretical Percent of Relief Flow	=B108/B17	0.4799	
110	Pressure Drop Across Relief Valve	=B102-B105	6.633	psi
111				

Maximum ECN Relief Flow Calculation 10/10/91

	A	B	C	D
112	ΔP Across Common Outlet to Cryocorner			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	7.99	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	0.473	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	0.007557	centipoise
126	Max. Mass Flow of Argon Gas	=B17	16130	lbm/hr
127	Max. Flow of Nitrogen Gas	=B189	3477	lbm/hr
128	Mass Flow of Mixture	=B126+B127	19608	lbm/hr
129	Reynolds Number	=6.31*B128/(B114*B125)	3840000	
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)	8.534	psi
134				

Maximum ECN Relief Flow Calculation 10/10/91

	A	B	C	D
135	ΔP from Cryocorner to Outside			Units
136	> Inner Pipe Diameter	0.53	0.53	f t
137	Inner Pipe Diameter (conv.)	=B136*12	6.36	in
138	> Equivalent Length	516	516	f t
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	0.473	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	0.007557	centipoise
149	Max. Mass Flow of Gas Mixture	=B128	19608	lbm/hr
150	Reynolds Number	=6.31*B149/(B137*B148)	2570000	
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)	2.022	psi
155				
156	Summation of Equivalent ΔPs			Units
157	Relief Valve Inlet Pressure Drop	=B33	1.852	psi
158	Relief Valve Outlet Pressure Drop	=B65	0.71	psi
159	Relief Valve Pressure Drop	=B110	6.633	psi
160	Relief Valve/Disk Branch	=B33+B65+B110	9.194	psi
161	Rupture Disk Inlet Pressure Drop	=B48	7.728	psi
162	Rupture Disk Outlet Pressure Drop	=B80	0.267	psi
163	Rupture Disk Pressure Drop	=B157+B158+B159-B161-B162	1.199	psi
164	Common Outlet Pressure Drop	=B133	8.534	psi
165	Cryocorner to Outside Pressure Drop	=B154	2.022	psi
166				

Maximum ECN Relief Flow Calculation 10/10/91

	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	8517	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	0.955	
175	gAr Flow Constant for Subsonic Flow(C1)	$= \text{SQRT}(2 * 32.2 / 1545 * (B168 / (B168 - 1)) * (B174^{(2/B168)} - B174^{(1/B168)}))$	0.042	
176	Flowing Inlet Pressure (Po)	=B4+14.696-B48	26.72	psia
177	> Molecular Weight of Argon	39.948	39.948	g/mol
178	Critical Pressure (Pcr)	=B169*B176	12.73	psia
179	Outlet Pressure (Pe) (using delta p's)	=14.696+B154+B133+B80	25.52	psia
180	Pressure Drop Across Rupture Disk	=B176-B179	1.199	psi
181	Maximum Theoretical Rupture Disk Flow	=B170*B173*B175*B176*SQRT(B177/B172)*60*60	8595	lbm/hr
182	Actual Rupture Disk Flow	=B43	8517	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			

Determine ECN Maximum Average Module Filling Temperature with Given Relieving Capacity

The worst case relieving scenario for any of the cryostats is when one of the adjacent vessels is full of LAr and accidentally discharges through the fill/drain line into a warm cryostat (note that this is a worse case than the storage dewar @ 20 psig filling a warm cryostat as in EN-321). The worst case overall is when the CC discharges liquid into the ECN. The following calculations given in a spreadsheet format with results listed to the right, determine the maximum module temperature that the ECN can be filled at without exceeding the capacity of the present relieving system. In this case the ECN has no accumulation of liquid argon and no allowance is given for the nitrogen cooling although it is assumed to be flowing in the manifold at ECN for back pressure calculations.

Other assumptions in this analysis include:

1. Pressure in the cryostat is 19.75 psig ($1.16 \times (\text{MAWP} + \text{FV})$).
2. Gaseous Nitrogen is concurrently flowing in the vent piping at a rate of 1608 lb/hr. This is derived from 0.3 gpm required for CC in its steady state mode and 4 gpm required for the concurrent cooldown (max.) of the ECS vessel.
3. Mixture mass flows are at their maximum at the junction of the relief device outlets on the ECN (GN2 mass flow actually increases gradually at junctions toward the ECS and there is a short segment of piping between the GAr outlets and the condenser exhaust).
4. The temperature in the vent piping is negligible since a large majority of this piping is insulated.
5. All flows are treated as incompressible (max. Mach No. < 0.3).
6. The temperature of the GN2 prior to mixing in the vent manifold is 84 K, saturated property at 2 atm.
7. Flow equations apply to weight-averaged mixture densities and viscosities.

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

For further information on the formulas used and the rationale for the calculations performed in each section, refer to EN-321, "Cryostat Filling Limitations for Proposed Ar Dewar Pressure Increase".

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 through 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 match 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.

Conclusions

Since the average module temperature in which the cryostat can be filled is *lower* than that calculated in EN-321, then this temperature appears to be the limiting case *for the cryostat*. Procedural safeguards coupled with locked switches on the output electrical signal to the fill valve PV118A I/P transmitter will be used to limit the filling of this cryostat to periods when the average temperature of the modules is 155 K or lower. This temperature limitation will probably be lower due to operational concerns and the structural safety of the cryostat modules.

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	155	155	K
3	> Max. Flow of Liquid Argon to Cryostat	18.4	18.4	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	6.927	6.927	mg/cc
10	*> gAr Density @ 2.4 bars	7.566	7.566	mg/cc
11	gAr Density @ 2.375 & Temp.	$=(B5-2.2)/0.2*(B10-B9)+B9$	7.486	mg/cc
12	gAr Density @ 2.375 bars (conv.)	$=B11/1000*62.428$	0.467	lbm/ft^3
13	Maximum Flow of Argon Gas	$=B3*B8/B11*1000$	3285	gpm
14	Maximum Flow of Argon Gas (conv.)	$=B13*0.13368$	439	cfm
15	Air Equivalent Flow @STP	$=6.32*B17*356/B16*SQRT(B99/(520*B177*28.97))$	1572	scfm air
16	Specific Heat Constant, C, for Ar	$=520*SQRT(B168*(2/(B168+1))^{((B168+1)/(B168-1)))}$	379	
17	Max. Mass Flow of Argon Gas	$=B14*B12*60$	12315	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.	$=(B5-2.2)/0.2*(B10-B9)+B9$	7.486	mg/cc
25	Ar Gas Density @ 2.375 bars (conv.)	$=B24/1000*62.428$	0.467	lbm/ft^3
26	*> gAr Viscosity @ 2.4 bars & Temp.	0.0001261	0.0001261	g/cm-s
27	gAr Viscosity @ 2.4 bars (conv.)	$=B26*100$	0.01261	centipoise
28	Max. Mass Flow to Relief Valve	$=B17*B18$	5911	lbm/hr
29	Reynolds Number	$=6.31*B28/(B22*B27)$	1200000	
30	> Relative Roughness (e/D)	0.0007	0.0007	
31	Friction Factor Guess	$=0.25*(LOG(B30/3.7+5.74/(B29^0.9)))^-2$	0.0185	
32	Friction Factor	$=0.25*(LOG(B30/3.7+2.51/(B29*B31^0.5)))^-2$	0.0184	
33	Pressure Drop	$=0.00000336*B32*B23*(B28^2)/B25/(B22^5)$	1.9	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	7.486	mg/cc
40	gAr Density @ 2.375 bars (conv.)	=B39/1000*62.428	0.467	lbm/ft^3
41	gAr Viscosity @ 2.4 bars	=B26	0.0001261	g/cm-s
42	gAr Viscosity @ 2.4 bars (conv.)	=B41*100	0.01261	centipoise
43	Max. Mass Flow to Rupture Disk	=B17*(1-B18)	6404	lbm/hr
44	Reynolds Number	=6.31*B43/(B37*B42)	1550000	
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	0.0194	
47	Friction Factor	=0.25*(LOG(B45/3.7+2.51/(B44*B46^0.5)))^-2	0.0194	
48	Pressure Drop	=0.0000336*B47*B38*(B43^2)/B40/(B37^5)	7.412	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.	6.292	6.292	mg/cc
57	gAr Density @ 2.0 bar (conv.)	=B56/1000*62.428	0.393	lbm/ft^3
58	*> gAr Viscosity @ 2.0 bar & Temp.	0.000126	0.000126	g/cm-s
59	gAr Viscosity @ 2.0 bar (conv.)	=B58*100	0.0126	centipoise
60	Max. Mass Flow to Relief Valve	=B28	5911	lbm/hr
61	Reynolds Number	=6.31*B60/(B54*B59)	908000	
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	0.0177	
64	Friction Factor	=0.25*(LOG(B62/3.7+2.51/(B61*B63^0.5)))^-2	0.0176	
65	Pressure Drop	=0.0000336*B64*B55*(B60^2)/B57/(B54^5)	0.728	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	6.292	mg/cc
72	gAr Density @ 2.0 bar (conv.)	=B71/1000*62.428	0.393	lbm/ft^3
73	gAr Viscosity @ 2.0 bar & Temp.	=B58	0.000126	g/cm-s
74	gAr Viscosity @ 2.0 bar (conv.)	=B73*100	0.0126	centipoise
75	Max. Mass Flow to Rupture Disk	=B43	6404	lbm/hr
76	Reynolds Number	=6.31*B75/(B69*B74)	1490000	
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	0.0194	
79	Friction Factor	=0.25*(LOG(B77/3.7+2.51/(B76*B78^0.5)))^-2	0.0194	
80	Pressure Drop	=0.00000336*B79*B70*(B75^2)/B72/(B69^5)	0.255	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	6.927	mg/cc
86	gAr Density @ 2.4 bars	=B10	7.566	mg/cc
87	gAr Density @ 2.375 & Temp.	=(B84-2.2)/0.2*(B86-B85)+B85	7.486	mg/cc
88	Temp. at Common Outlet	=(B2*B17+84*B189)/(B17+B189)	139	K
89	> Pressure to Calculate Density	1.5	1.5	bars
90	*> gAr Density @ 1.5 bars & New Temp.	5.265	5.265	mg/cc
91	*> gAr Viscosity @ 1.5 bars & New Temp.	0.0001133	0.0001133	g/cm-s
92	gAr Viscosity @ 1.5 bar (conv.)	=B91*100	0.01133	centipoise
93				

Maximum Module Temperature Calculation 10/17/91

	A	B	C	D
94	ΔP Across Relief Valve			Units
95	> Critical Ratio (P_{cr}/P_1) for Argon	0.487	0.487	
96	> Specific Heat Ratio (k) for Argon	=B168	1.69	
97	> Area of 2" x 3" Relief Valve	2.29	2.29	in ²
98	Flow Through Relief Valve	=B28	5911	lbm/hr
99	Flowing Temperature	=1.8*B2	279	deg R
100	> Compressibility Factor	1	1	
101	> Nozzle Coefficient for type 93T	0.939	0.939	
102	Flowing Inlet Pressure (P_1)	=B4+14.696-B33	32.55	psia
103	> Molecular Weight of Argon	39.948	39.95	g/mol
104	Critical Pressure (P_{cr})	=B95*B102	15.85	psia
105	Outlet Pressure (P_2) (using delta p's)	=14.696+B154+B133+B65	26.05	psia
106	Pressure Ratio (P_2/P_1)	=(B102-0.55*((B102-B105)^0.98))/B102	0.894	
107	Theoretical Factor (F^*) (using P_2)	=SQRT(((B96/(B96-1))*(B106^(2/B96)-B106^((B96+1)/B96))))	0.309	
108	Max. Theoretical Relief Flow (using F^*)	=735*B97*B101*B102*B107*SQRT(B103/B99/B100)	6021	lbm/hr
109	Theoretical Percent of Relief Flow	=B108/B17	0.4889	
110	Pressure Drop Across Relief Valve	=B102-B105	6.494	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	5.265	mg/cc
117	gAr Density @ 1.5 bar (conv.)	=B116/1000*62.428	0.329	lbm/ft^3
118	*> gN2 Gas Density @ 1.5 bar & New Temp.	3.72712	3.727	mg/cc
119	gN2 Gas Density @ 1.5 bar (conv.)	=B118/1000*62.428	0.233	lbm/ft^3
120	Gas Mixture Density @1.5 bar	=(B17*B117+B127*B119)/B128	0.308	lbm/ft^3
121	gAr Viscosity @ 1.5 bar & New Temp.	=B91	0.0001133	g/cm-s
122	gAr Viscosity @ 1.5 bar (conv.)	=B121*100	0.01133	centipoise
123	*> gN2 Viscosity @ 1.5 bar & New Temp.	0.000093482	0.00009348	g/cm-s
124	gN2 Viscosity @ 1.5 bar (conv.)	=B123*100	0.009348	centipoise
125	Mixture Viscosity @1.5 bar	=(B17*B122+B127*B124)/B128	0.01089	centipoise
126	Max. Mass Flow of Argon Gas	=B17	12315	lbm/hr
127	Max. Flow of Nitrogen Gas	=B189	3477	lbm/hr
128	Mass Flow of Mixture	=B126+B127	15793	lbm/hr
129	Reynolds Number	=6.31*B128/(B114*B125)	2150000	
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	0.0163	
132	Friction Factor	=0.25*(LOG(B130/3.7+2.51/(B129*B131^0.5)))^-2	0.0162	
133	Pressure Drop	=0.00000336*B132*B115*(B128^2)/B120/(B114^5)	8.579	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	5.265	mg/cc
140	gAr Gas Density @ 1.5 bar (conv.)	=B139/1000*62.428	0.329	lbm/ft^3
141	gN2 Gas Density @ 1.5 bar & New Temp.	=B118	3.727	mg/cc
142	gN2 Gas Density @ 1.5 bar (conv.)	=B141/1000*62.428	0.233	lbm/ft^3
143	Gas Mixture Density @1.5 bar	=(B17*B140+B189*B142)/B149	0.308	lbm/ft^3
144	gAr Viscosity @ 1.5 bar & New Temp.	=B121	0.0001133	g/cm-s
145	gAr Viscosity @ 1.5 bar (conv.)	=B144*100	0.01133	centipoise
146	gN2 Viscosity @ 1.5 bar & New Temp.	=B123	0.00009348	g/cm-s
147	gN2 Viscosity @ 1.5 bar (conv.)	=B146*100	0.009348	centipoise
148	Gas Mixture Viscosity @1.5 bar	=(B17*B145+B189*B147)/B149	0.01089	centipoise
149	Max. Mass Flow of Gas Mixture	=B128	15793	lbm/hr
150	Reynolds Number	=6.31*B149/(B137*B148)	1440000	
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	0.0153	
153	Friction Factor	=0.25*(LOG(B151/3.7+2.51/(B150*B152^0.5)))^-2	0.0152	
154	Pressure Drop	=0.00000336*B153*B138*(B149^2)/B143/(B137^5)	2.049	psi
155				
156	Summation of Equivalent ΔPs			Units
157	Relief Valve Inlet Pressure Drop	=B33	1.9	psi
158	Relief Valve Outlet Pressure Drop	=B65	0.728	psi
159	Relief Valve Pressure Drop	=B110	6.494	psi
160	Relief Valve/Disk Branch	=B33+B65+B110	9.122	psi
161	Rupture Disk Inlet Pressure Drop	=B48	7.412	psi
162	Rupture Disk Outlet Pressure Drop	=B80	0.255	psi
163	Rupture Disk Pressure Drop	=B157+B158+B159-B161-B162	1.455	psi
164	Common Outlet Pressure Drop	=B133	8.579	psi
165	Platform to Outside Pressure Drop	=B154	2.049	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)	1.691	1.691	
169	Critical Ratio	$= (2 / (B168 + 1))^{(B168 / (B168 - 1))}$	0.484	
170	> Area of 3" Rupture Disk	$= 3.14159 * (3^2) / 4$	7.069	in^2
171	Flow Through Rupture Disk	=B43	6404	lbm/hr
172	Flowing Temperature	=1.8*B2	279	deg R
173	> ASME Coefficient (K)	0.62	0.62	
174	Pressure Ratio (Pe/Po)	=B179/B176	0.946	
175	gAr Flow Constant for Subsonic Flow(C1)	$= \text{SQRT}(2 * 32.2 / 1545 * (B168 / (B168 - 1)) * (B174^{(2 / B168)} - B174))$	0.046	
176	Flowing Inlet Pressure (Po)	=B4+14.696-B48	27.03	psia
177	> Molecular Weight of Argon	39.948	39.948	g/mol
178	Critical Pressure (Pcr)	=B169*B176	13.08	psia
179	Outlet Pressure (Pe) (using delta p's)	=14.696+B154+B133+B80	25.58	psia
180	Pressure Drop Across Rupture Disk	=B176-B179	1.455	psi
181	Maximum Theoretical Rupture Disk Flow	=B170*B173*B175*B176*SQRT(B177/B172)*60*60	7458	lbm/hr
182	Actual Rupture Disk Flow	=B43	6404	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 temperature			
194				
195	> indicates variable not requiring change for new			
196	temperature			
197				
198	(conv.) indicates the previous value converted to new			
199	units			

**Calculation of Max. Flowrate
from CC to ECN**

$$d = 1.682 \text{ in} = 0.1402 \text{ ft}$$

[1 1/2" SCH. 10 inner pipe dia.]

$$A = 0.01543 \text{ ft}^2$$

[cross-sectional area]

Max. CC Flow to ECN, 10/10/91

John Wu

Reference: drawings from Tony Parker	CC drain line	ECN drain line	TOTAL
# of elbows, 90°	8	19	27
# of elbows, 45°	1	1	2
# of tees, branch	1	0	1
# of tees, thru	1	0	1

Calculation of Equivalent Length

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

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

$$L_{1.7'' \text{ dia.}} = 6.8 \text{ ft} + 8.3 \text{ ft (CC drain line)} + 21.7 \text{ ft (CC to rotary bayonet assembly)} + 4.6 \text{ ft} + 5.2 \text{ ft (rotary U-tube dimensions)} + 6.1 \text{ ft} + 13 \text{ ft (ECN drain line)} = 65.7 \text{ ft total.}$$

Equivalent lengths of the two flowmeters are accounted for by including two 4 foot lengths 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)

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

$$L_{\text{piping}} = 65.7 \text{ ft} + 2(42.4 \text{ ft}) = 150.5 \text{ ft total}$$

Convert elbows and tees into equivalent lengths of pipe.

$$L_{\text{fittings}} = [27(20) + 2(14) + 1(60) + 1(20)] \times 0.1402 \text{ ft} = 90.8 \text{ ft}$$

$$L_{\text{eq}} = 150.5 \text{ ft} + 90.8 \text{ ft} = \mathbf{241.3 \text{ ft}}$$

Calculation of Resistance Coefficient

Reference: Crane Technical Paper No. 410

Calculate the resistance coefficient for the piping and fittings.

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

let $f = 0.02136$ [friction factor guess]

$$K_{\text{piping, fittings}} = 0.02136 \left(\frac{241.3 \text{ ft}}{0.1402 \text{ ft}} \right) = 36.76$$

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

$$K_{\text{inlet}} = 0.5$$

$$K_{\text{outlet}} = 1.0$$

Calculate resistance coefficient for the valves, where C_v , the valve coefficient, is 34 for PV218A (CC), and 41 for PV118A (ECN).

$$K_{\text{valves}} = \left(\frac{29.9 d^2}{C_v} \right)^2 = \left(\frac{29.9 (1.682)^2}{34} \right)^2 + \left(\frac{29.9 (1.682)^2}{41} \right)^2 = 10.45$$

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

$$\Sigma K = 36.76 + 1.5 + 10.45 = \mathbf{48.71}$$

Driving Pressure

Calculate the differential pressure available under relieving conditions.

max. head available = 17 ft (CC completely full)

Calculate the pressure due to the head.

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 = 17 ft x 0.580 psi/ft = 9.86 psi

$$\begin{aligned}\Delta p_{\text{relieving}} &= (\text{CC pressure}) - (\text{ECN pressure}) + (\text{head pressure}) \\ &= 27.7 \text{ psia} - 34.45 \text{ psia} + 9.86 \text{ psi} = 3.11 \text{ psid}\end{aligned}$$

$$\Delta p_{\text{available}} = \Delta p_{\text{relieving}} = 3.11 \text{ psid}$$

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 .

$$v = \sqrt{\frac{2 g_c (144 \Delta p)}{\rho \Sigma K}} = \sqrt{\frac{2 \left(32.174 \frac{\text{lb}_m \cdot \text{ft}}{\text{lb}_f \cdot \text{s}^2} \right) \left(144 \frac{\text{in}^2}{\text{ft}^2} \right) \Delta p_{\text{available}}}{\left(83.47 \frac{\text{lb}_m}{\text{ft}^3} \right) (48.71)}}$$

$$v = 1.510 \sqrt{\Delta p_{\text{available}}}$$

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

$$v = 1.510 \sqrt{\Delta p_{\text{available}}} = 1.510 \sqrt{3.11} = 2.663 \frac{\text{ft}}{\text{s}}$$

Max. CC Flow to ECN, 10/10/91

John Wu

Solve for q , the flow rate in cfs:

$$q = Av = \left(0.01543 \text{ ft}^2\right) \left(2.663 \frac{\text{ft}}{\text{s}}\right) = 0.0411 \text{ cfs}$$

Convert q to gpm:

$$q = 0.0411 \frac{\text{ft}^3}{\text{sec}} \times \frac{\text{gal}}{0.13368 \text{ ft}^3} \times \frac{60 \text{ sec}}{\text{min}}$$

$$q = 18.45 \text{ gpm}$$

Check Friction Factor

$$\text{Re}_{\text{relieving}} = \frac{\rho V_{\text{rel}} d}{\mu}$$

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

$$q_{\text{relieving}} = 18.45 \text{ gpm}$$

$$v_{\text{relieving}} = 2.663 \text{ ft/s (from before)}$$

$$\text{Re}_{\text{relieving}} = \frac{\left(83.47 \frac{\text{lb}_m}{\text{ft}^3}\right) \left(2.663 \frac{\text{ft}}{\text{s}}\right) (0.1402 \text{ ft})}{1.6252 \times 10^{-4} \frac{\text{lb}_m}{\text{ft-s}}} = 1.918 \times 10^5$$

Assuming a value of 0.00015 roughness for commercial steel pipe, the relative roughness is 0.001, and the friction factor is 0.02136, which agrees with the assumption.

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 CC. 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 lbf-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 CC 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
27		Els90			number of 90° elbows
2		Els45			number of 45° elbows
1		TeesBr			number of tees, branch
1		TeesTh			number of tees, thru
150.5		Lpiping		ft	equivalent length of 1.7" piping
		Lfittin	90.828	ft	equivalent length of fittings
		Leq	241.328	ft	equivalent length
		f	.02135622		friction factor (guess)
.5		Kinlet			inlet resistance
1		Koutlet			outlet resistance
		Kpiping	36.769466		resistance of piping
34		CvofCC			coeff. of CC valve
41		CvofECN			coeff. of ECN valve
		Kvalves	10.446724		resistance of valves
		SumK	48.71619		summation of resistances
17		elev		ft	max. head available
83.47		rho		lbm/ft^3	density of argon
		SpWt	.57965278	psi/ft	specific weight of argon
		DPhead	9.8540972	psi	delta p from head
		DPrel	3.1040972	psi	delta p relieving
		DPavail	3.1040972	psi	delta p available
		Vrel	2.6595892	ft/s	relieving velocity
		Re	191462.14		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	18.419523	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 = (29.9*(D^2)/CvofCC)^2 + (29.9*(D^2)/CvofECN)^2      "resistance of
* 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 = -19.75 + 13 + DPhead      "delta p due to elevation difference
* DPavail = DPrel      "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

```

SUBJECT

CC MAX LN₂ FLOW

NAME

RUSS RUCINSKI

DATE

10-18-90

REVISION DATE

11/19/90

FROM COMPARING EQUIVALENT LENGTHS, IT IS CLEAR THAT ALMOST ALL PRESSURE DROP WILL OCCUR ACROSS PV-201N. PV-201-N WITH $C_v = 1.25$ WILL LIMIT LN₂ FLOW.

*** The same argument will apply to PV101N on the ECN
KD 14 Aug 91

DRIVING PRESSURE

DURING COOLDOWN THE LN₂ DEWAR PRESSURE IS 70 PSIA
[REFERENCE CC CRYOSTAT PROCEDURES PAR. 7.4.1]

HEAD DUE TO ELEVATION

ELEVATION LN₂ DEWAR $\Rightarrow$ 749'-0"

DIA. OF LN₂ DEWAR = 8.3 FT

ELEVATION TOP OF LN₂ IN DEWAR IS 753'-2"

ELEVATION OF CC CONDENSING COILS IS 731'-2"

---

22 FT.

CONVERT THIS HEAD TO PSI

$$22 \text{ FT} \times \rho_{\text{LN}_2} (\text{PRESS} = 44 \text{ PSIA}) = 22 \text{ FT} \cdot \left(47.2 \frac{\text{lbm}}{\text{ft}^3} \right) \left(\frac{1 \text{ FT}^2}{144 \text{ in}^2} \right)$$

$$= 7.2 \text{ PSI}$$

$$\text{DRIVING PRESSURE} = (\text{LN}_2 \text{ DEWAR PRESS.}) + (\text{HEAD}) - [\text{CC HAMP} + 3 \text{ PSI}]$$

$$= (70 \text{ PSIA}) + (7.2 \text{ PSI}) - [30 \text{ PSIA} + 3 \text{ PSI}]$$

$$\Delta P_{\text{MAX}} = 44.2 \text{ PSI}$$

SUBJECT

CC. MAX. LN₂ FLOW

NAME

RUSS RUCINSKI

DATE

11/19/90

REVISION DATE

50685E.D&S
10/18/90 P. 5CALCULATE MAXIMUM FLOW

ASSUMPTIONS:

- 1) CONDENSOR COMPLETELY SEVERED
- 2) NEGLECT HEAT LEAK IN TRANSFER LINE
- 3) PRESSURE DROP THRU LINE IS NEGLIGIBLE (CONSERVATIVE)
12/ PV-201-N LIMITS FLOW
- 4) SATURATED LN₂

REFERENCE: FLOW EQUATIONS FOR SIZING CONTROL VALVES

ISA STANDARD * ISA-S75.01-1985

SECTION 5 APPLIES, INCOMPRESSIBLE FLUID - CHOKED FLOW OF VAPORIZING LIQUID (FLASHING ACROSS PV-201-N)

$$q_{\max} = N_1 F_L C_V \sqrt{\frac{P_1 - F_F P_V}{G_F}}$$

WHERE N_1 = Numerical constant $N_1 = 1.00$ FOR $q = \text{gpm}$ & $p = \text{psia}$ $F_L = 0.9$ APPENDIX D, GLOBE VALVE F_L = LIQ. PRESS. RECOVER. P_1 = UPSTREAM PRESSURE, PSIA. P_2 = DOWNSTREAM PRESSURE, PSIA

$$P_{VC} = F_F P_V$$

 P_V = ABS. VAPOR PRESSURE AT INLET

$$F_F = 0.96 - 0.28 \left(\frac{P_V}{P_C} \right)^{1/2}$$

APPENDIX G.

 P_C = ABSOLUTE CRITICAL PRESSURE G_F = SPECIFIC GRAVITYSOLUTION

$$P_1 = 77.2 \text{ PSIA} \quad P_2 = 33 \text{ PSIA} \quad P_V = 70 \text{ PSIA} \quad C_V = 1.25$$

$$P_C = 493.13 \text{ PSIA}$$

$$F_F = 0.96 - 0.28 \left(\frac{70}{493.13} \right)^{1/2} = .8545$$

$$P_{VC} = F_F P_V = .8545 (70 \text{ PSIA}) = 59.815 \text{ PSIA}$$

$$q_{\max} = (1.0)(.9)(1.25) \sqrt{\frac{77.2 - .8545(70)}{.998 \text{ g/cc}}} = 5.50 \text{ gpm}$$

CONVERTING TO g/s;

$$q_{\max} = 5.50 \frac{\text{gal}}{\text{min}} \times .727 \frac{\text{g}}{\text{cm}^3} \times \frac{1 \text{ min}}{60 \text{ s}} \times \frac{3.785 \cdot 4 \text{ cm}^3}{1 \text{ gal}} = 252 \frac{\text{g}}{\text{s}}$$

Using Anderson Greenwood equations: $V = 6.32 q_{\max} / M$

$$V_{\text{air}} = V \sqrt{M_{\text{air}} / M_{\text{LN}_2}}$$

$$\therefore V_{\text{air}} = 443 \text{ SCFM}$$

References

1. Introduction to Fluid Mechanics, 3rd Ed., Robert W. Fox, Alan T. McDonald, John Wiley & 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.
5. "Cryostat Filling Limitations for Proposed Ar Dewar Pressure Increase", DØ Engineering Note #3740-EN-321, J. Wu/K. Dixon, Jul., 1991.
6. "Calorimeter Conduction, Radiation and Fire Loads", DØ Engineering Note #3740-EN-6, S. J. Wintercorn, May, 1985.

Vacuum Vessel Engineering Note
(per Mandatory Standard SD-41)

Prepared By Kelly Dixon Date 20 Aug 91 Div/Sect RD/Dφ
Reviewed By [Signature] Date 10-29-91 Div/Sect AD/Cryogenics
Div/Dept Head [Signature] Date 10-29-91 Div/Sect Res Div.

I. Identification and Verification of Compliance

Fill in the Fermilab Engineering Conformance Label information below:

This vessel conforms to Engineering Standard SD-41

Vessel Title North Endcap Calorimeter (NEC) ChgoutVessel Number ~~RD 4025~~ RD 9000 ^{J.W. 11/11/91}Vessel Drawing Number 3740.220-ME-222256Working Temperature Range -320 °F 150 °FDesigner/Manufacturer Process Engineering, Inc.Date of Manufacture June 1990

Acceptance Date _____

Director's signature (or designee) if vessel is for manned area and requires an exception to the provisions of this standard.

Amendment No.:

Reviewed By:

Date:

_____	_____	_____
_____	_____	_____
_____	_____	_____

II. Description of Vessel and Relief System

Laboratory location code DAB

Laboratory property number _____

Purpose of vessel Insulating jacket for cryostat

List all pertinent drawings (append copies)

Drawing No.:

Location of Original:

3740.220-ME-222256Dφ Files, DAB3740.224-ME-273065Dφ Files, DAB3740.224-ME-273030Dφ Files, DAB

Can this vessel be pressurized? _____

If yes, to what pressure. _____

Is a testing procedure necessary for the safe acceptance testing (proof testing) of this vessel? _____

If yes, supply the written procedure with this Engineering Note.

Is an operating procedure necessary for the safe operation of this vessel? _____

If yes, supply the written procedure with this Engineering Note.

List all reliefs and settings. Provide a schematic of the relief system components, and appropriate calculations or test results to prove that overpressurization beyond the maximum allowable internal pressure will not occur.

Manufacturer	Relief	Setting	Flow Rate	Size	ASME Stamped Device Yes/No
<u>FNAL</u>	<u>TOP parallel flat plate</u>	<u>0.16</u>	<u>—</u>	<u>4" ID Port</u>	<u>No</u>
	<u>BOTTOM parallel flat plate</u>	<u>0.07</u>	<u>—</u>	<u>10" ID Port</u>	<u>No</u>
_____	_____	_____	_____	_____	_____
_____	_____	_____	_____	_____	_____

Welding Information

Has the vessel been fabricated in a Fermilab shop? Yes _____ No _____

If "Yes", append a copy of the welding shop statement of welder qualification.

VACUUM VESSEL RELIEF

- DETERMINE RELIEVING PRESSURE

FLAT ALUMINUM PLATE, 11" O.D. x 11/16" THICK

$$WT. = 6.3 \text{ lbs}$$

SEALING SIDE O-RING @ 7.125" DIA.

$$A = \pi D^2/4 = 39.9 \text{ in}^2$$

$$\text{LIFTING PRESSURE} = \frac{6.3 \text{ lbs}}{39.9 \text{ in}^2} = \underline{0.16 \text{ psig}}$$

CONCLUSION

GO WITH ^{O.D.} 15/16 X .080 DIA. WIRE SPRING X 2 1/32"
OVERALL LENGTH. 16 lb/in RATING. FROM
McMASTER CARR, # 9658K46, \$.88/each

USE 5 ~~WASHERS~~ WASHERS, FINAL STOCK 1218-0720

AND 5/8 X 2" STAINLESS STEEL SHOULDER BOLTS
FROM PRESTIGE PARTS. 1/2-13 THREAD.

SPRING COMPRESSION WILL BE $.078 \times \frac{5}{4} + \frac{1}{32} = .42125"$
WHICH GIVES ~~5.44~~ 6.74 lbs FORCE/BOLT
26.96 ~~134.8~~ lbs OVER ALL UPWARD FORCE WITH
NO VACUUM.

RELIEF PLATE WILL WEIGH

$$21.6 \text{ lbs} - .23 = 21.37 \text{ lbs}$$

↑
HOLES

5.6 lbs DIFFERENCE UP UNDER NO VACUUM

RELIEF PLATE WILL DROP AT

$$\frac{5.6 \text{ lb}}{78.5 \text{ in}^2} = .07 \text{ psid.}$$

**Calculation of Cross-sectional Area
Required for Vacuum Jacket Relief**

References: "Pressure Relief Device Standards", CGA S-1.3-1980

"Standard for Insulated Cargo Tank Specification

for Cryogenic Liquids", CGA-341-1987

Calculate the current area available from the relief devices:

$$A_{\text{avail}}^{\text{disc}} = 0.785 (10^2 + 4^2) = 91 \text{ in}^2$$

From the references, the required area is:

$$A_{\text{req'd}}^{\text{disc}} = 0.00024 \text{ in}^2 / \text{lb}_m \text{ H}_2\text{O capacity}$$

Assume a volume of 3000 gallons of H₂O, as a conservative calculation.

Calculate the total mass of H₂O:

$$3000 \text{ gal} \times \frac{0.13368 \text{ ft}^3}{\text{gal}} \times \frac{62.4 \text{ lb}_m}{\text{ft}^3} = 25,000 \text{ lb}_m \text{ H}_2\text{O}$$

Calculate the required area of the reliefs:

$$A_{\text{req'd}}^{\text{disc}} = \frac{0.00024 \text{ in}^2}{\text{lb}_m \text{ H}_2\text{O}} \times 25,000 \text{ lb}_m \text{ H}_2\text{O}$$

$$A_{\text{req'd}}^{\text{disc}} = 6 \text{ in}^2$$

Since the calculated available area of the reliefs far exceeds the required area, the vacuum vessel is adequately protected from overpressurization. The relief devices installed are parallel plate relief devices (10" and 4"), so the actual area available is not the entire area of the disc, however, the available area calculated is large enough for small errors.