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Pressure Relief for RHIC Cryogenic System

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December 1993

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

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AD/RHIC/RD-64

RHIC PROJECT

Brookhaven National Laboratory

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PRESSURE RELIEF FOR RHIC CRYOGENIC SYSTEM

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The maximum credible accident for the RHIC magnet cryostats has been identified with a heat load extrapolated from the loss of vacuum experiment for RHIC dipole magnet DRD-009 in MAGCOOL. The venting requirements for each of the cryogenic lines was evaluated and the corresponding pressure drops calculated. The resultant pressure relief system complies with the guideline given by UG-125 paragraph c 2 Section VIII of ASME Pressure Vessel Code. Detailed analysis and results are given.

1). MECHANISM

The relief system is designed to prevent overpressure in the cryogenic system. Should the massive heat input from a catastrophic loss of vacuum occur, cold helium will be heated through a constant density process to higher pressures at a rapid rate. When the pressure reaches the relief setting, helium will be vented outside and the process becomes a constant pressure heating process as illustrated in Fig. 1.

LOSS OF VACUUM

------> HEATING AT CONSTANT DENSITY

------> PRESSURE INCREASE

------> VENTING WITH HEATING AT CONSTANT PRESSURE

Figure 1. Heating and venting process for pressure relief

2). HEAT LOAD

The most important parameter in designing a relief system is the heating rate. However uncertainties associated with the heat load in an accident are usually large and a maximum credible accident (MCA) must be defined. In RHIC, the longest section of cryostats without a vacuum break occurs in the section from the position of insertion quadrupole Q4 at one end of a sextant to Q4 at the other (See RHIC Design Manual, Table 3-6) and is about 500 meters long. Within this common vacuum envelope, there are cooling passages in the magnets and three lines (the supply line, the return line and the utility line) operated at 4.5 K and one shield line at 55 K. The MCA heat load is extrapolated from the catastrophic loss of vacuum experiments performed with a RHIC dipole in MAGCOOL[1,2,3] by considering the MCA of the system for loss of vacuum to air and to helium respectively.

In the present study, the heat load from air entering the vacuum space is dominated by cryopumping or condensation of air. It is independent of the length of the magnet and equals 11 kW per cm^2 of the cross sectional area through which air may enter. The MCA for loss of insulating vacuum to air is assumed to come from an opening of 5.08 cm diameter and 20 cm^2 cross sectional area. The corresponding heat load to the magnet cooling circuit and the three lines at 4.5 K equals 220 kW.

The heat load from helium entering the vacuum space, however, is mainly from conduction and convection, and is proportional to the heat transfer area in each case. From the tests performed in MAGCOOL, the heat load to the magnet cooling passages and the supply line for one dipole, one feed can and one end can with a total length of 12.5 meter equaled 10 kW. Eight kW of this heat load is assumed to go to the magnet cooling passages and 2 kW is assumed to go to the supply line because the magnet has four times the surface area of the supply line.

The total heat load for the 500 meter section is assumed to be 40 times that of the MAGCOOL results. Thus the magnet cooling passages have a 320 kW heat load. The supply line has an 80 kW heat load. The return and the utility lines are also assumed each to have an 80 kW heat load. The total heat load to the 4.5 K system of a sextant then totals 560 kW.

The heat load to the shield is assumed to be 40 times the 6.7 kW heat load derived from the loss of vacuum experiment with a RHIC dipole performed previously with helium in the insulating vacuum. The total heat load to the shield in a sextant is 270 kW. A summary of the MCA heat load for the magnet cooling passages, the supply line, the return line, the utility line and the shield line for loss of vacuum with helium is given in Table 1.

Table 1. The MCA heat load for the RHIC cryogenic system

	Magnet cooling passages	Supply line	Return line	Utility line	Heat Shield line
Heat Load kW	320	80	80	80	270

3). VENTING OF HELIUM

With the MCA heat input, a relief system can be sized provided the heat absorbing capability of the cryogenic system is known. The pressure rise rate before a cryogenic system reaches the relief pressure depends on the heat absorbing capability of the constant density heating process. The amount of helium that must be vented outside depends on the heat absorbing of the cryogenic system during the venting process. The required venting capacity equals to the heating rate divided by the heat absorbing rate during a constant pressure process as will be explained below.

The RHIC cryogenic system in the ring is designed to relieve pressure at 18.7 atmospheres. No liquid-vapor phase change occurs during the venting process. The heating process from thermodynamic state 1 at the relief pressure to state x at a higher temperature and the relief pressure with helium venting through a relief valve can be explained by Fig. 2.[4]

m_1		m_x		(m_1-m_x)
P_1	$\rightarrow$	P_x	+	$P_x=P_1$
T_1		T_x		$T_1 \rightarrow T_x$
h_1		h_x		$h_1 \rightarrow h_x$
ρ_1		ρ_x		$\rho_1 \rightarrow \rho_x$
State 1		*State x*		*Helium Relieved Through Safety Device*

Fig. 2 Heating process from state 1 to x with helium venting through relief.

where P is the pressure
T is the temperature
m is the mass of helium
h is the enthalpy
ρ is the density
and subscripts 1 and x refer to thermodynamic states 1 and x.

The heat absorbed by the helium vapor for any such incremental step can be approximated by eqn. 1. The heat absorbed per unit mass of helium leaving the container from state 1 to state x is given by eqn. 2.

$$q = m_x \, (h_x - h_1) + (m_1 - m_x) \, \frac{(h_x - h_1)}{2} \tag{1}$$

$$L' = \frac{q}{(m_1 - m_x)} = \frac{(h_x - h_1)\,(m_1 + m_x)}{2\,(m_1 - m_x)} \tag{2}$$

where m , h , 1 and x are as defined above
and q is heat absorbed
L' is the heat absorbed per unit mass of helium leaving the container

The amount of helium that must be vented equals the heat input rate divided by the heat absorbed per unit of helium gas leaving the system as shown in eqn. 3.

$$\dot{m}_{vent} = \dot{Q} \,/\, L' \qquad (3)$$

where $\dot{Q}$ is the heating rate.
$\dot{m}$ is the helium flow, lb/hr.
and subscript *vent* refers to the helium vented through the relief.

The relief valve can be sized from the pressure, temperature and flow requirements according to formulas given by the valve manufacturer. Eqn. 4 is given by the Anderson, Greenwood and Co., and a suitable set of units[5] must be adopted.

$$A = \frac{\dot{m}_{vent} \sqrt{T}}{C\ K\ P\ \sqrt{M}} \qquad (4)$$

where A is the orifice area of the relief, in^2.
T is the inlet temperature, in degree R.
C is the gas constant, 377 for helium.
K is the valve coefficient of discharge = 0.816.
P is the pressure of the gas flow, lb/in^2.
and M is the molecular weight of gas, 4 for helium.

Calculations have been performed for the relief valves of the magnet cooling passages, the supply line, the return line, the utility line and the shield line. The results are given in Table 2 later in this study. Since it is desirable to have the relief valves located near the end of the sextant where penetrations from the cold region to the ambient can be incorporated more conveniently, the pressure drop in the long helium passages should be investigated so that nowhere in the sextant will excessive pressure build up. Also since these calculations do not consider the warmup of cold helium, the piping length to the relief valve should be kept to a minimum.

4). PRESSURE DROPS

The pressure drop calculation in the present study is quite complicated because the flow rate varies with length. In addition, there is a large variation in the flow area in the magnet cooling passages, particularly in the 50 watt recoolers. The pressure drop calculations are divided into two categories, one with a constant and one with a variable flow area. In both cases, the flow rate increases linearly with the path length because venting of helium is caused by the increase in heat load which is assumed to be equally distributed along the sextant.

For the supply, the return, the utility and the shield lines, the flow area does not vary with length. The relief valves for these lines are assumed to be installed at the two ends of a sextant one each at a 50 m distance from the end magnet. The flow path is, thus, 300 meters long. A simplified procedure is developed for estimating the pressure drops. The procedure divides the flow passage into twenty segments. The helium flow in the first segment equals one twentieth the total flow. The flow in the second segment equals two twentieths of the flow. The flow in each segment increases linearly with the number of the segment. The flow in the 20th segment equals the total flow. The total pressure drop equals the summation of pressure drops in the twenty segments as given in eqn. 5. The total pressure drop equals 7.2 times the pressure drop for the total flow through one segment.

$$\begin{aligned} \Delta P_{Total} &= \sum \Delta P_i \\ &= f \frac{L_i\, \dot{m}_{vent}^2}{2\, d_i\, \rho\, g\, A^2} \left[\left(\frac{1}{20}\right)^2 + \left(\frac{2}{20}\right)^2 + \cdots + \left(\frac{20}{20}\right)^2 \right] \\ &= f \frac{L_i\, \dot{m}_{vent}^2}{2\, d_i\, \rho\, g\, A^2}\, 7.2 \end{aligned} \tag{5}$$

where f is the friction factor
d is the hydraulic diameter
L is the length of a segment
A is the cross sectional area for helium flow
and g is acceleration of gravity

For the magnet cooling passages, there is large difference in flow area. The pressure drop is calculated from the layout of the magnet string including dipoles, quadrupoles, interconnects, recoolers, etc. The flow also increases with the flow path. The results suggest that venting at intermediate points of the sextant can be avoided by locating four relief valves in the magnet cooling passage. Two will be at locations similar to those for the several lines and one each will be located between dipole D9 and quadrupole Q9 in the RHIC magnet lattice at each end of the sextant. With four relief valves, the maximum pressure drop in a sextant is about 2.2 atms. Detailed results are given in Appendix 2. The largest pressure drop for the magnet cooling passage under the condition that one of the four relief valve fails to open has also been calculated and given in Table 2.

5.) RESULTS

Using the MCA heat load, the 18.7 atm (275 psia) relief pressure, and the initial conditions and the geometry of the cryogenic system, the relief requirements have been calculated for each of the supply, return, utility and shield lines and the magnet cooling passages. The detailed results for both constant density and constant pressure heating processes are given in Appendix 1. A summary of the requirements for these relief valves and conditions at which they operate are given below in Table 2. In the Table 2, the pressure drops at design conditions as well as when only one relief valve fails to open are also given. As one can see, the pressure drops in this system certainly comply with the 21% maximum allowable working pressure guideline per UG-125 paragraph c.2 of ASME Pressure Vessel Code Section VIII Division 1.[6] Even when only one relief valve fails to open, the pressure drops are manageable.

Table 2. Requirements and operating conditions of the relief valves

Line	MCA Heat Load kW	Total Area of Relief in^2	Temp. Relief Opens K	Max. Mass Flow g/s	Press. Drop Design atm	Press. Drop with one relief fails to open atm
Supply	80	0.28	7.3	1353	0.05	0.36
Return	80	0.13	54	269	0.02	0.14
Utility	80	0.13	54	269	0.02	0.14
Shield	270	0.38	68	728	0.47	3.24
Magnet	320	1.11	7.3	5411	2.2	4.2

6). VALVE SELECTIONS

The uncertainties in the calculations associated with the catastrophic loss of vacuum are large. Redundant valves will also be required as back-up in the event of a possible mechanical failure of a valve. Relief valves larger than those calculated shall be used and the system shall be designed to have enough capacity to prevent excessive pressure build up should any relief valve fails to open.

Since the magnet cooling passages, the supply line, the return line, the utility line and the shield line are independent, at least four relief valves shall be installed for the magnet cooling passages and two relief valves in each of the several lines. The relief valve system shall have the required capacity plus some safety margin in the event that any one valve in the system fails. A preliminary valve selection based on the Anderson, Greenwood and Co. catalog is given in Table 3.

Table 3. Preliminary valve selection for a sextant based on A, G & Co. catalog series 80

Line	Valve	Orifice Size in^2	No. Used	Safety Factor	Locations
Supply	G series	0.503	2	3.6	valve boxes
Return	F series	0.307	2	4.7	valve boxes
Utility	F series	0.307	2	4.7	valve boxes
Shield	G series	0.503	2	2.7	valve boxes
Magnet	G series	0.503	4	1.8	valve boxes and between D9 and Q9

7). CONCLUSION

The maximum credible accident for the RHIC magnet cryostats has been identified with a heat load extrapolated from the loss of vacuum experiment for RHIC dipole magnet DRD-009 in MAGCOOL. The venting requirements for each of the cryogenic lines was evaluated and the corresponding pressure drops calculated. The results show the pressure drop in this system is less than the 21 % maximum allowable working pressure guideline for multiple relief valves with unexpected source of heat load given by UG-125 paragraph c.2 Section VIII Division 1 of ASME Pressure Vessel Code.

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2. K. C. Wu, D. P. Brown, J. Sondericker and D. Zantopp, "An experimental study using helium to produce a catastrophic loss of vacuum in a RHIC dipole magnet cryostat", RHIC Project Tech. Note AD/RHIC/RD-54, Feb. 1993.
3. K. C. Wu, D. P. Brown, J. Sondericker and D. Zantopp, "An experimental study of catastrophic loss of vacuum for RHIC dipole in MAGCOOL", presented in the CEC-ICMC conference, July 12-16, Albuquerque, N.M.
4. R. H. Kropschot, B. W. Birmingham and D. B. Mann, "Technology of Liquid Helium", National Bureau of Standards, Monograph 111, Oct. 1968.
5. "SERIES 80 SAFETY-RELIEF VALVES", Catalog 1800, Anderson, Greenwood & Co., May 1974.
6. ASME PRESSURE VESSELS Section VIII Div. 1, 1992.

APPENDIX 1:

Requirements and operating conditions for the relief valves of the RHIC cryogenic system

Please enter remarks
Size relief valve for RHIC supply line S
Enter initial pressure, temperature, volume, relief pressure,
heating rate, half sextant length and equivalent pipe diameter
p0-atm
5
to-K
4.5
vol-L
2655
pvent-atm
18.7
qheat-kW
80
length-m
350
dia-cm
6.8

Constant density heating process

p	t	rho	M	u	d-time
atm	K	g/cc	kg	j/g	sec.
5.00	4.50	.137	364.8	8.42	
6.37	4.78	.137	364.8	9.08	3.01
7.74	5.06	.137	364.8	9.80	3.26
9.11	5.34	.137	364.8	10.52	3.31
10.48	5.63	.137	364.8	11.21	3.12
11.85	5.91	.137	364.8	11.90	3.13
13.22	6.19	.137	364.8	12.59	3.15
14.59	6.47	.137	364.8	13.28	3.18
15.96	6.75	.137	364.8	13.99	3.21
17.33	7.02	.137	364.8	14.64	2.99
18.70	7.30	.137	364.8	15.36	3.27

Constant pressure venting process

												Pres drop		Air
t1	rho1	h1	tx	rhox	hx	heatl	L	Gi	mout	Area	dt	1/2	1 sext	Cap.
K	g/cc	j/g	K	g/cc	j/g	j/g	B/lb		g/s	in**2	sec	atm	atm	SCFM
7.3	.137	29.2	8.3	.126	34.1	60.	26.	22.	1322.	.24	21.8	.04	.27	985.
8.3	.126	34.1	9.3	.115	39.9	59.	25.	24.	1353.	.26	23.2	.04	.31	1066.
9.3	.115	39.9	10.3	.103	46.5	59.	25.	25.	1352.	.27	23.8	.05	.34	1121.
10.3	.103	46.5	11.3	.091	53.6	61.	26.	26.	1309.	.28	22.8	.05	.36	1137.
11.3	.091	53.6	12.3	.082	60.6	64.	28.	26.	1244.	.27	20.1	.05	.36	1128.
12.3	.082	60.6	13.3	.074	67.3	68.	29.	25.	1170.	.27	17.4	.05	.36	1103.
13.3	.074	67.3	14.3	.068	73.8	72.	31.	25.	1104.	.26	15.2	.05	.36	1079.
14.3	.068	73.8	15.3	.062	80.1	77.	33.	25.	1044.	.26	13.7	.05	.35	1055.
15.3	.062	80.1	16.3	.058	86.5	82.	35.	24.	974.	.25	12.7	.05	.34	1017.
16.3	.058	86.5	18.3	.050	98.9	90.	39.	23.	887.	.24	22.4	.05	.32	980.
18.3	.050	98.9	20.3	.045	111.1	101.	44.	22.	790.	.22	19.1	.04	.29	920.
20.3	.045	111.1	22.3	.040	123.0	113.	49.	21.	711.	.21	16.7	.04	.27	867.
22.3	.040	123.0	24.3	.037	134.6	124.	53.	20.	646.	.20	14.9	.04	.26	823.
24.3	.037	134.6	26.3	.034	146.1	135.	58.	19.	592.	.19	13.4	.03	.24	784.
26.3	.034	146.1	28.3	.031	157.5	147.	63.	18.	546.	.18	12.2	.03	.23	751.
28.3	.031	157.5	30.3	.029	168.7	158.	68.	17.	507.	.18	11.2	.03	.22	722.
30.3	.029	168.7	32.3	.027	179.8	169.	73.	17.	474.	.17	10.4	.03	.21	696.
32.3	.027	179.8	34.3	.025	190.8	180.	78.	16.	444.	.16	9.6	.03	.20	673.
34.3	.025	190.8	36.3	.024	201.8	191.	82.	16.	419.	.16	9.0	.03	.19	652.
36.3	.024	201.8	38.3	.023	212.7	202.	87.	15.	396.	.15	8.5	.03	.18	634.

Please enter remarks
Size relief valve for RHIC return line R
Enter initial pressure, temperature, volume, relief pressure,
heating rate, half sextant length and equivalent pipe diameter

p0-atm
1

to-K
4.3

vol-L
3265

pvent-atm
18.7

qheat-kW
80

length-m
350

dia-cm
6.8

Constant density heating process

p atm	t K	rho g/cc	M kg	u j/g	d-time sec.
1.00	4.30	.016	52.6	24.55	
2.77	9.31	.016	52.6	40.33	10.37
4.54	14.33	.016	52.6	55.84	10.20
6.31	19.31	.016	52.6	71.38	10.22
8.08	24.29	.016	52.6	86.98	10.26
9.85	29.28	.016	52.6	102.61	10.28
11.62	34.31	.016	52.6	118.39	10.38
13.39	39.29	.016	52.6	134.04	10.29
15.16	44.36	.016	52.6	149.97	10.47
16.93	49.32	.016	52.6	165.55	10.24
18.70	54.39	.016	52.6	181.47	10.47

Constant pressure venting process

t1 K	rho1 g/cc	h1 j/g	tx K	rhox g/cc	hx j/g	heatl j/g	L B/lb	Gi	mout g/s	Area in**2	dt sec	Pres drop 1/2 atm	Pres drop 1 sext atm	Air Cap. SCFM
54.4	.016	299.1	55.4	.016	304.4	297.	128.	12.	269.	.13	3.5	.02	.14	518.
55.4	.016	304.4	56.4	.016	309.7	302.	130.	12.	265.	.13	3.4	.02	.14	514.
56.4	.016	309.7	57.4	.015	315.0	308.	133.	12.	260.	.12	3.3	.02	.14	509.
57.4	.015	315.0	58.4	.015	320.3	313.	135.	12.	256.	.12	3.3	.02	.14	505.
58.4	.015	320.3	59.4	.015	325.6	318.	137.	12.	251.	.12	3.2	.02	.14	501.
59.4	.015	325.6	60.4	.015	330.9	324.	139.	11.	247.	.12	3.2	.02	.13	497.
60.4	.015	330.9	61.4	.014	336.2	329.	142.	11.	243.	.12	3.1	.02	.13	493.
61.4	.014	336.2	62.4	.014	341.5	334.	144.	11.	239.	.12	3.1	.02	.13	489.
62.4	.014	341.5	63.4	.014	346.8	339.	146.	11.	236.	.12	3.0	.02	.13	485.
63.4	.014	346.8	65.4	.013	357.3	347.	150.	11.	230.	.12	5.9	.02	.13	481.
65.4	.013	357.3	67.4	.013	367.9	358.	154.	11.	223.	.12	5.7	.02	.13	474.
67.4	.013	367.9	69.4	.013	378.4	369.	159.	11.	217.	.11	5.5	.02	.12	467.
69.4	.013	378.4	71.4	.012	388.9	379.	163.	10.	211.	.11	5.4	.02	.12	461.
71.4	.012	388.9	73.4	.012	399.5	390.	168.	10.	205.	.11	5.2	.02	.12	455.
73.4	.012	399.5	75.4	.012	410.0	400.	172.	10.	200.	.11	5.1	.02	.12	449.
75.4	.012	410.0	77.4	.011	420.5	411.	177.	10.	195.	.11	5.0	.02	.12	443.
77.4	.011	420.5	79.4	.011	431.0	421.	181.	10.	190.	.11	4.8	.02	.11	437.
79.4	.011	431.0	81.4	.011	441.4	432.	186.	10.	185.	.11	4.7	.02	.11	432.
81.4	.011	441.4	83.4	.011	451.9	442.	191.	10.	181.	.10	4.6	.02	.11	427.
83.4	.011	451.9	85.4	.010	462.4	453.	195.	9.	177.	.10	4.5	.02	.11	422.

Please enter remarks
Size relief valve for RHIC utility line U
Enter initial pressure, temperature, volume, relief pressure,
heating rate, half sextant length and equivalent pipe diameter
p0-atm
1
to-K
4.3
vol-L
2655
pvent-atm
18.7
qheat-kW
80
length-m
350
dia-cm
6.8

Constant density heating process

p atm	t K	rho g/cc	M kg	u j/g	d-time sec.
1.00	4.30	.016	42.8	24.55	
2.77	9.31	.016	42.8	40.33	8.44
4.54	14.33	.016	42.8	55.84	8.29
6.31	19.31	.016	42.8	71.38	8.31
8.08	24.29	.016	42.8	86.98	8.34
9.85	29.28	.016	42.8	102.61	8.36
11.62	34.31	.016	42.8	118.39	8.44
13.39	39.29	.016	42.8	134.04	8.37
15.16	44.36	.016	42.8	149.97	8.51
16.93	49.32	.016	42.8	165.55	8.33
18.70	54.39	.016	42.8	181.47	8.52

Constant pressure venting process

t1 K	rho1 g/cc	h1 j/g	tx K	rhox g/cc	hx j/g	heatl j/g	L B/lb	Gi	mout g/s	Area in**2	dt sec	Pres drop 1/2 atm	1 sext atm	Air Cap. SCFM
54.4	.016	299.1	55.4	.016	304.4	297.	128.	12.	269.	.13	2.8	.02	.14	518.
55.4	.016	304.4	56.4	.016	309.7	302.	130.	12.	265.	.13	2.8	.02	.14	514.
56.4	.016	309.7	57.4	.015	315.0	308.	133.	12.	260.	.12	2.7	.02	.14	509.
57.4	.015	315.0	58.4	.015	320.3	313.	135.	12.	256.	.12	2.7	.02	.14	505.
58.4	.015	320.3	59.4	.015	325.6	318.	137.	12.	251.	.12	2.6	.02	.14	501.
59.4	.015	325.6	60.4	.015	330.9	324.	139.	11.	247.	.12	2.6	.02	.13	497.
60.4	.015	330.9	61.4	.014	336.2	329.	142.	11.	243.	.12	2.5	.02	.13	493.
61.4	.014	336.2	62.4	.014	341.5	334.	144.	11.	239.	.12	2.5	.02	.13	489.
62.4	.014	341.5	63.4	.014	346.8	339.	146.	11.	236.	.12	2.4	.02	.13	485.
63.4	.014	346.8	65.4	.013	357.3	347.	150.	11.	230.	.12	4.8	.02	.13	481.
65.4	.013	357.3	67.4	.013	367.9	358.	154.	11.	223.	.12	4.6	.02	.13	474.
67.4	.013	367.9	69.4	.013	378.4	369.	159.	11.	217.	.11	4.5	.02	.12	467.
69.4	.013	378.4	71.4	.012	388.9	379.	163.	10.	211.	.11	4.4	.02	.12	461.
71.4	.012	388.9	73.4	.012	399.5	390.	168.	10.	205.	.11	4.2	.02	.12	455.
73.4	.012	399.5	75.4	.012	410.0	400.	172.	10.	200.	.11	4.1	.02	.12	449.
75.4	.012	410.0	77.4	.011	420.5	411.	177.	10.	195.	.11	4.0	.02	.12	443.
77.4	.011	420.5	79.4	.011	431.0	421.	181.	10.	190.	.11	3.9	.02	.11	437.
79.4	.011	431.0	81.4	.011	441.4	432.	186.	10.	185.	.11	3.8	.02	.11	432.
81.4	.011	441.4	83.4	.011	451.9	442.	191.	10.	181.	.10	3.7	.02	.11	427.
83.4	.011	451.9	85.4	.010	462.4	453.	195.	9.	177.	.10	3.6	.02	.11	422.

Please enter remarks
Size relief valve for RHIC shield line H
Enter initial pressure, temperature, volume, relief pressure,
heating rate, half sextant length and equivalent pipe diameter
p0-atm
15
to-K
55
vol-L
1804
pvent-atm
18.7
qheat-kW
270
length-m
350
dia-cm
5.4

Constant density heating process

p atm	t K	rho g/cc	M kg	u j/g	d-time sec.
15.00	55.00	.013	23.2	183.92	
15.37	56.31	.013	23.2	188.04	.35
15.74	57.63	.013	23.2	192.15	.35
16.11	59.03	.013	23.2	196.57	.38
16.48	60.34	.013	23.2	200.68	.35
16.85	61.66	.013	23.2	204.80	.35
17.22	62.97	.013	23.2	208.91	.35
17.59	64.28	.013	23.2	213.03	.35
17.96	65.69	.013	23.2	217.44	.38
18.33	67.00	.013	23.2	221.55	.35
18.70	68.31	.013	23.2	225.67	.35

Constant pressure venting process

t1 K	rho1 g/cc	h1 j/g	tx K	rhox g/cc	hx j/g	heatl j/g	L B/lb	Gi	mout g/s	Area in**2	dt sec	Pres drop 1/2 atm	Pres drop 1 sext atm	Air Cap. SCFM
68.3	.013	372.7	69.3	.013	378.0	371.	160.	11.	728.	.38	.5	.47	3.24	1567.
69.3	.013	378.0	70.3	.013	383.3	376.	162.	11.	718.	.38	.4	.46	3.21	1556.
70.3	.013	383.3	71.3	.012	388.5	381.	164.	10.	708.	.38	.4	.46	3.18	1546.
71.3	.012	388.5	72.3	.012	393.8	387.	167.	10.	698.	.37	.4	.46	3.15	1535.
72.3	.012	393.8	73.3	.012	399.0	392.	169.	10.	689.	.37	.4	.45	3.12	1525.
73.3	.012	399.0	74.3	.012	404.3	397.	171.	10.	680.	.37	.4	.45	3.09	1515.
74.3	.012	404.3	75.3	.012	409.5	402.	173.	10.	671.	.37	.4	.44	3.06	1505.
75.3	.012	409.5	76.3	.012	414.8	408.	176.	10.	662.	.36	.4	.44	3.04	1496.
76.3	.012	414.8	77.3	.011	420.0	413.	178.	10.	654.	.36	.4	.44	3.01	1486.
77.3	.011	420.0	79.3	.011	430.5	421.	181.	10.	642.	.36	.8	.43	2.97	1477.
79.3	.011	430.5	81.3	.011	441.0	431.	186.	10.	626.	.36	.8	.42	2.92	1459.
81.3	.011	441.0	83.3	.011	451.5	442.	190.	10.	611.	.35	.8	.42	2.88	1442.
83.3	.011	451.5	85.3	.010	462.0	452.	195.	9.	597.	.35	.7	.41	2.83	1425.
85.3	.010	462.0	87.3	.010	472.5	463.	199.	9.	583.	.34	.7	.41	2.79	1409.
87.3	.010	472.5	89.3	.010	482.9	473.	204.	9.	571.	.34	.7	.40	2.75	1394.
89.3	.010	482.9	91.3	.010	493.4	484.	208.	9.	558.	.34	.7	.39	2.71	1379.
91.3	.010	493.4	93.3	.010	503.9	494.	213.	9.	546.	.33	.7	.39	2.67	1364.
93.3	.010	503.9	95.3	.009	514.3	505.	217.	9.	535.	.33	.7	.38	2.63	1350.
95.3	.009	514.3	97.3	.009	524.8	515.	222.	9.	524.	.33	.6	.38	2.60	1337.
97.3	.009	524.8	99.3	.009	535.2	526.	226.	9.	514.	.32	.6	.37	2.57	1324.

Please enter remarks
Size relief valve for RHIC Magnet Cooling Passages M
Enter initial pressure, temperature, volume, relief pressure,
heating rate, half sextant length and equivalent pipe diameter

p0-atm
5
to-K
4.5
vol-L
5335
pvent-atm
18.7
qheat-kW
320
length-m
350
dia-cm
5.4

Constant density heating process

p	t	rho	M	u	d-time
atm	K	g/cc	kg	j/g	sec.
5.00	4.50	.137	733.1	8.42	
6.37	4.78	.137	733.1	9.08	1.51
7.74	5.06	.137	733.1	9.80	1.64
9.11	5.34	.137	733.1	10.52	1.66
10.48	5.63	.137	733.1	11.21	1.57
11.85	5.91	.137	733.1	11.90	1.57
13.22	6.19	.137	733.1	12.59	1.58
14.59	6.47	.137	733.1	13.28	1.60
15.96	6.75	.137	733.1	13.99	1.61
17.33	7.02	.137	733.1	14.64	1.50
18.70	7.30	.137	733.1	15.36	1.64

Constant pressure venting process

t1	rho1	h1	tx	rhox	hx	heatl	L	Gi	mout	Area	dt	Air Cap.
K	g/cc	j/g	K	g/cc	j/g	j/g	B/lb		g/s	in**2	sec	SCFM
7.3	.137	29.2	8.3	.126	34.1	60.	26.	22.	5290.	.96	10.9	3939.
8.3	.126	34.1	9.3	.115	39.9	59.	25.	24.	5411.	1.04	11.7	4265.
9.3	.115	39.9	10.3	.103	46.5	59.	25.	25.	5408.	1.09	12.0	4486.
10.3	.103	46.5	11.3	.091	53.6	61.	26.	26.	5236.	1.11	11.4	4550.
11.3	.091	53.6	12.3	.082	60.6	64.	28.	26.	4977.	1.10	10.1	4512.
12.3	.082	60.6	13.3	.074	67.3	68.	29.	25.	4682.	1.07	8.7	4413.
13.3	.074	67.3	14.3	.068	73.8	72.	31.	25.	4417.	1.05	7.6	4317.
14.3	.068	73.8	15.3	.062	80.1	77.	33.	25.	4174.	1.03	6.9	4221.
15.3	.062	80.1	16.3	.058	86.5	82.	35.	24.	3896.	.99	6.4	4066.
16.3	.058	86.5	18.3	.050	98.9	90.	39.	23.	3546.	.95	11.2	3922.
18.3	.050	98.9	20.3	.045	111.1	101.	44.	22.	3158.	.90	9.6	3678.
20.3	.045	111.1	22.3	.040	123.0	113.	49.	21.	2842.	.84	8.4	3470.
22.3	.040	123.0	24.3	.037	134.6	124.	53.	20.	2583.	.80	7.5	3291.
24.3	.037	134.6	26.3	.034	146.1	135.	58.	19.	2366.	.76	6.7	3137.
26.3	.034	146.1	28.3	.031	157.5	147.	63.	18.	2184.	.73	6.1	3004.
28.3	.031	157.5	30.3	.029	168.7	158.	68.	17.	2029.	.70	5.6	2887.
30.3	.029	168.7	32.3	.027	179.8	169.	73.	17.	1895.	.68	5.2	2784.
32.3	.027	179.8	34.3	.025	190.8	180.	78.	16.	1778.	.65	4.8	2692.
34.3	.025	190.8	36.3	.024	201.8	191.	82.	16.	1675.	.63	4.5	2609.
36.3	.024	201.8	38.3	.023	212.7	202.	87.	15.	1584.	.62	4.3	2534.

APPENDIX 2:

Pressure drop calculations in the magnet cooling passages

```
Calculate the pressure drop in a RHIC string with uniform temperature distributi
Enter 11 for constant flow condition
Enter 22 for flow increase with distance such as
          occur in a loss of vacuum situation
22
Select the starting and the ending magnets

  I Item    I Item    I Item    I Item    I Item    I Item    I Item    I Item
  1  SP3    2  D0     3  INT    4  Q1     5  INT    6  Q2     7  INT    8  Q3
  9  SP2   10  Q4    11  INT   12  Q5    13  INT   14  D5    15  INT   16  Q6
 17  REC   18  INT   19  D6    20  INT   21  Q7    22  INT   23  Q8    24  SP1
 25  INT   26  Q9    27  INT   28  D9    29  INT   30  Q10   31  INT   32  D10
 33  INT   34  Q11   35  INT   36  D11   37  INT   38  Q12   39  INT   40  D12
 41  INT   42  Q13   43  INT   44  D13   45  INT   46  Q14   47  REC   48  INT
 49  D14   50  INT   51  Q15   52  INT   53  D15   54  INT   55  Q16   56  INT
 57  D16   58  INT   59  Q17   60  INT   61  D17   62  INT   63  Q18   64  INT
 65  D18   66  INT   67  Q19   68  INT   69  D19   70  INT   71  Q20   72  INT
 73  D20   74  INT   75  Q21   76  REC   77  INT   78  D20   79  INT   80  Q20
 81  INT   82  D19   83  INT   84  Q19   85  INT   86  D18   87  INT   88  Q18
 89  INT   90  D17   91  INT   92  Q17   93  INT   94  D16   95  INT   96  Q16
 97  INT   98  D15   99  INT  100  Q15  101  INT  102  D14  103  INT  104  Q14
105  REC  106  INT  107  D13  108  INT  109  Q13  110  INT  111  D12  112  INT
113  Q12  114  INT  115  D11  116  INT  117  Q11  118  INT  119  D10  120  INT
121  Q10  122  INT  123  D9   124  INT  125  Q9   126  INT  127  SP1  128  Q8
129  INT  130  Q7   131  INT  132  D6   133  INT  134  Q6   135  REC  136  INT
137  D5   138  INT  139  Q5   140  INT  141  Q4   142  SP2  143  Q3   144  INT
145  Q2   146  INT  147  Q1   148  INT  149  D0   150  SP3  151  END  152  END

Enter I1 and I2 for the starting and ending magents
75
124
Enter the total flow in g/s
5400
Enter inlet pressure in atm
21
Enter inlet temperature in K
7.3

Do you satisfy this input ? (y/n)
y

 No of arc magnets between Q21 and  INT
 equals  24

           RHIC   flow  pres.   pres.
          comp.   rate          drop
                  g/s    atm    atm
            Q21    86.  21.00  .0002
            REC    86.  21.00  .0037
            INT    86.  21.00  .0000
            D20   171.  21.00  .0016
            INT   171.  20.99  .0001
            Q20   257.  20.99  .0017
            INT   257.  20.99  .0002
            D19   343.  20.99  .0059
            INT   343.  20.99  .0004
            Q19   429.  20.99  .0045
            INT   429.  20.98  .0006
            D18   514.  20.98  .0128
            INT   514.  20.97  .0008
```

Q18	600.	20.97	.0086
INT	600.	20.96	.0011
D17	686.	20.96	.0223
INT	686.	20.94	.0014
Q17	771.	20.93	.0141
INT	771.	20.92	.0018
D16	857.	20.92	.0343
INT	857.	20.88	.0022
Q16	943.	20.88	.0209
INT	943.	20.86	.0027
D15	1029.	20.86	.0490
INT	1029.	20.81	.0032
Q15	1114.	20.81	.0290
INT	1114.	20.78	.0038
D14	1200.	20.77	.0662
INT	1200.	20.71	.0044
Q14	1286.	20.70	.0385
REC	1286.	20.66	.7843
INT	1286.	19.88	.0051
D13	1371.	19.87	.0868
INT	1371.	19.79	.0058
Q13	1457.	19.78	.0498
INT	1457.	19.73	.0066
D12	1543.	19.73	.1096
INT	1543.	19.62	.0074
Q12	1629.	19.61	.0622
INT	1629.	19.55	.0082
D11	1714.	19.54	.1351
INT	1714.	19.40	.0091
Q11	1800.	19.39	.0761
INT	1800.	19.32	.0101
D10	1886.	19.31	.1634
INT	1886.	19.14	.0111
Q10	1971.	19.13	.0914
INT	1971.	19.04	.0121
D9	2057.	19.03	.1945
INT	2057.	18.84	.0132

Total pressure drop equals 2.178 atm

Do you want another calculation (y/n) ?
y

Calculate the pressure drop in a RHIC string with uniform temperature distributi
Enter 11 for constant flow condition
Enter 22 for flow increase with distance such as
occur in a loss of vacuum situation
22
Select the starting and the ending magnets

I	Item	I	Item	I	Item	I	Item	I	Item	I	Item	I	Item	I	Item
1	SP3	2	D0	3	INT	4	Q1	5	INT	6	Q2	7	INT	8	Q3
9	SP2	10	Q4	11	INT	12	Q5	13	INT	14	D5	15	INT	16	Q6
17	REC	18	INT	19	D6	20	INT	21	Q7	22	INT	23	Q8	24	SP1
25	INT	26	Q9	27	INT	28	D9	29	INT	30	Q10	31	INT	32	D10
33	INT	34	Q11	35	INT	36	D11	37	INT	38	Q12	39	INT	40	D12
41	INT	42	Q13	43	INT	44	D13	45	INT	46	Q14	47	REC	48	INT
49	D14	50	INT	51	Q15	52	INT	53	D15	54	INT	55	Q16	56	INT
57	D16	58	INT	59	Q17	60	INT	61	D17	62	INT	63	Q18	64	INT
65	D18	66	INT	67	Q19	68	INT	69	D19	70	INT	71	Q20	72	INT
73	D20	74	INT	75	Q21	76	REC	77	INT	78	D20	79	INT	80	Q20
81	INT	82	D19	83	INT	84	Q19	85	INT	86	D18	87	INT	88	Q18
89	INT	90	D17	91	INT	92	Q17	93	INT	94	D16	95	INT	96	Q16
97	INT	98	D15	99	INT	100	Q15	101	INT	102	D14	103	INT	104	Q14
105	REC	106	INT	107	D13	108	INT	109	Q13	110	INT	111	D12	112	INT
113	Q12	114	INT	115	D11	116	INT	117	Q11	118	INT	119	D10	120	INT
121	Q10	122	INT	123	D9	124	INT	125	Q9	126	INT	127	SP1	128	Q8
129	INT	130	Q7	131	INT	132	D6	133	INT	134	Q6	135	REC	136	INT
137	D5	138	INT	139	Q5	140	INT	141	Q4	142	SP2	143	Q3	144	INT
145	Q2	146	INT	147	Q1	148	INT	149	D0	150	SP3	151	END	152	END

Enter I1 and I2 for the starting and ending magents
88
28
Enter the total flow in g/s
5400
Enter inlet pressure in atm
23
Enter inlet temperature in K
7.3

Do you satisfy this input ? (y/n)
y

No of arc magnets between Q18 and D9
equals 30

RHIC comp.	flow rate g/s	pres. atm	pres. drop atm
Q18	86.	23.00	.0002
INT	86.	23.00	.0000
D18	171.	23.00	.0016
INT	171.	23.00	.0001
Q19	257.	23.00	.0016
INT	257.	23.00	.0002
D19	343.	23.00	.0058
INT	343.	22.99	.0004
Q20	429.	22.99	.0044
INT	429.	22.99	.0006
D20	514.	22.99	.0125
INT	514.	22.97	.0008
REC	514.	22.97	.1234

Q21	600.	22.85	.0084
INT	600.	22.84	.0011
D20	686.	22.84	.0219
INT	686.	22.82	.0014
Q20	771.	22.82	.0138
INT	771.	22.80	.0018
D19	857.	22.80	.0337
INT	857.	22.77	.0022
Q19	943.	22.76	.0204
INT	943.	22.74	.0027
D18	1029.	22.74	.0480
INT	1029.	22.69	.0032
Q18	1114.	22.69	.0284
INT	1114.	22.66	.0037
D17	1200.	22.66	.0648
INT	1200.	22.59	.0043
Q17	1286.	22.59	.0377
INT	1286.	22.55	.0049
D16	1371.	22.55	.0842
INT	1371.	22.46	.0056
Q16	1457.	22.46	.0483
INT	1457.	22.41	.0064
D15	1543.	22.40	.1062
INT	1543.	22.30	.0071
Q15	1629.	22.29	.0603
INT	1629.	22.23	.0080
D14	1714.	22.22	.1309
INT	1714.	22.09	.0088
REC	1714.	22.08	1.3710
Q14	1800.	20.71	.0748
INT	1800.	20.63	.0099
D13	1886.	20.62	.1607
INT	1886.	20.46	.0109
Q13	1971.	20.45	.0898
INT	1971.	20.36	.0119
D12	2057.	20.35	.1912
INT	2057.	20.16	.0130
Q12	2143.	20.15	.1063
INT	2143.	20.04	.0141
D11	2229.	20.03	.2248
INT	2229.	19.80	.0153
Q11	2314.	19.79	.1245
INT	2314.	19.66	.0166
D10	2400.	19.65	.2614
INT	2400.	19.38	.0179
Q10	2486.	19.37	.1442
INT	2486.	19.22	.0192
D9	2571.	19.20	.3014

Total pressure drop equals 4.098 atm

Do you want another calculation (y/n) ?
y

```
Calculate the pressure drop in a RHIC string with uniform temperature distributi
Enter 11 for constant flow condition
Enter 22 for flow increase with distance such as
          occur in a loss of vacuum situation
22
Select the starting and the ending magnets

  I Item    I Item    I Item    I Item    I Item    I Item    I Item    I Item
  1  SP3    2  D0     3  INT    4  Q1     5  INT    6  Q2     7  INT    8  Q3
  9  SP2   10  Q4    11  INT   12  Q5    13  INT   14  D5    15  INT   16  Q6
 17  REC   18  INT   19  D6    20  INT   21  Q7    22  INT   23  Q8    24  SP1
 25  INT   26  Q9    27  INT   28  D9    29  INT   30  Q10   31  INT   32  D10
 33  INT   34  Q11   35  INT   36  D11   37  INT   38  Q12   39  INT   40  D12
 41  INT   42  Q13   43  INT   44  D13   45  INT   46  Q14   47  REC   48  INT
 49  D14   50  INT   51  Q15   52  INT   53  D15   54  INT   55  Q16   56  INT
 57  D16   58  INT   59  Q17   60  INT   61  D17   62  INT   63  Q18   64  INT
 65  D18   66  INT   67  Q19   68  INT   69  D19   70  INT   71  Q20   72  INT
 73  D20   74  INT   75  Q21   76  REC   77  INT   78  D20   79  INT   80  Q20
 81  INT   82  D19   83  INT   84  Q19   85  INT   86  D18   87  INT   88  Q18
 89  INT   90  D17   91  INT   92  Q17   93  INT   94  D16   95  INT   96  Q16
 97  INT   98  D15   99  INT  100  Q15  101  INT  102  D14  103  INT  104  Q14
105  REC  106  INT  107  D13  108  INT  109  Q13  110  INT  111  D12  112  INT
113  Q12  114  INT  115  D11  116  INT  117  Q11  118  INT  119  D10  120  INT
121  Q10  122  INT  123  D9   124  INT  125  Q9   126  INT  127  SP1  128  Q8
129  INT  130  Q7   131  INT  132  D6   133  INT  134  Q6   135  REC  136  INT
137  D5   138  INT  139  Q5   140  INT  141  Q4   142  SP2  143  Q3   144  INT
145  Q2   146  INT  147  Q1   148  INT  149  D0   150  SP3  151  END  152  END

Enter I1 and I2 for the starting and ending magents
88
150
Enter the total flow in g/s
5400
Enter inlet pressure in atm
23
Enter inlet temperature in K
7.3

Do you satisfy this input ? (y/n)
y

  No of arc magnets between Q18 and  SP3
  equals  26

            RHIC   flow   pres.   pres.
           comp.   rate           drop
                    g/s     atm    atm
             Q18    86.   23.00  .0002
             INT    86.   23.00  .0000
             D17   171.   23.00  .0016
             INT   171.   23.00  .0001
             Q17   257.   23.00  .0016
             INT   257.   23.00  .0002
             D16   343.   23.00  .0058
             INT   343.   22.99  .0004
             Q16   429.   22.99  .0044
             INT   429.   22.99  .0006
             D15   514.   22.99  .0125
             INT   514.   22.97  .0008
             Q15   600.   22.97  .0084
```

```
INT    600.  22.96  .0011
D14    686.  22.96  .0218
INT    686.  22.94  .0014
Q14    771.  22.94  .0138
REC    771.  22.93  .2760
INT    771.  22.65  .0018
D13    857.  22.65  .0337
INT    857.  22.61  .0022
Q13    943.  22.61  .0205
INT    943.  22.59  .0027
D12   1029.  22.59  .0481
INT   1029.  22.54  .0032
Q12   1114.  22.54  .0284
INT   1114.  22.51  .0037
D11   1200.  22.51  .0649
INT   1200.  22.44  .0043
Q11   1286.  22.44  .0377
INT   1286.  22.40  .0050
D10   1371.  22.39  .0844
INT   1371.  22.31  .0056
Q10   1457.  22.30  .0484
INT   1457.  22.25  .0064
D9    1543.  22.25  .1064
INT   1543.  22.14  .0071
Q9    1629.  22.13  .0604
INT   1629.  22.07  .0080
SP1   1629.  22.07  .0179
Q8    1714.  22.05  .0656
INT   1714.  21.98  .0088
Q7    1800.  21.97  .0690
INT   1800.  21.91  .0097
D6    1886.  21.90  .1583
INT   1886.  21.74  .0107
Q6    1971.  21.73  .0780
REC   1971.  21.65 1.8250
INT   1971.  19.82  .0120
D5    2057.  19.81  .1101
INT   2057.  19.70  .0131
Q5    2143.  19.69  .1002
INT   2143.  19.59  .0142
Q4    2229.  19.57  .1117
SP2   2229.  19.46  .0518
Q3    2229.  19.41  .1124
INT   2229.  19.30  .0154
Q2    2229.  19.28  .1258
INT   2229.  19.16  .0155
Q1    2229.  19.14  .1096
INT   2229.  19.03  .0155
D0    2229.  19.02  .1304
SP3   2229.  18.89  .0661

Total pressure drop equals  4.180 atm

Do you want another calculation (y/n) ?
n

C:\FORTRAN\NBSDIST>
```