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Process Performance and Carnot Efficiency for RHIC Refrigerator

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August 1994

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC/RD-74

RHIC PROJECT

Brookhaven National Laboratory

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The process requirements for RHIC refrigerator under three cases of heat load have been calculated. Case 1 is for baseline heat load (as August 1994) and requires approximately 60% of the installed compressor capacity. Case 2 and 3 are "High Liquefaction" and "High Refrigeration" loads and the compressor is fully loaded. The flow diagram for the RHIC refrigerator is given in Fig. 1. The process points and the refrigerator performance for these three cases are given in Appendix 1A, 1B, 2A, 2B, 3A and 3B.

The heat load for the RHIC refrigeration system consists of the primarily heat load at 4.5 K, the shield heat load between 40 to 70 K and the liquefaction load for magnet power leads. The Carnot work or theoretical minimum work for each load is considered.

The Carnot work W_{carnot} required to absorb heat Q_L at temperature T_L to higher temperature T_H equal to Q_H - Q_L, where

$$Q_H = Q_L \frac{T_H}{T_L} \qquad (1)$$

Therefore,

$$W_{carnot} = Q_L \left[\frac{T_H}{T_L} - 1 \right] \qquad (2)$$

In the present study, T_H is the ambient temperature and is assumed to be 305 K. For 4.5 K heat load (T_L= 4.5),

$$\frac{W_{carnot}}{Q_L} = \frac{305}{4.5} - 1 = 66.8 \ watt\ per\ watt \qquad (3)$$

For shield load (assuming the mean temperature is 55 K),

$$\frac{W_{carnot}}{Q_L} = \frac{305}{55} - 1 = 4.55 \ watt\ per\ watt \qquad (4)$$

If one assumes the refrigerator has the same the efficiency at 4.5 K and at 55 K, then 1 watt of cooling at 55 K can be considered as equivalent to 0.068 watt of cooling at 4.5 K. However in RHIC, the shield cooling is provided by a high pressure flow. The theoretical minimum work should be evaluated from the change of Exergy to account for the pressure drops. The exergy is defined as [T_H s - h], where s is entropy and h is enthalpy. The supply and return flow conditions for the shield flow in RHIC baseline design are given in equation 5.

$$
\begin{array}{ll}
Flow = 404.3\ g/s & \\
P_{in} = 15.67\ atm & P_{out} = 9.67\ atm \\
T_{in} = 40\ K & T_{out} = 65.81\ K \\
h_{in} = 222\ J/g & h_{out} = 358\ J/g \\
s_{in} = 15.2\ J/g\text{-}K & s_{out} = 18.8\ J/g\text{-}K \\
E_{in} = 4399\ J/g & E_{out} = 5376\ J/g
\end{array}
\tag{5}
$$

The ratio for the exergy change to the enthalpy change equal to

$$
\frac{E_{out} - E_{in}}{h_{out} - h_{in}} = 7.18\ watt\ per\ watt \tag{6}
$$

The exergy analysis gives a higher work required compare to the formula of $T_H / T_L - 1$. On the average, 1 watt of shield load is equivalent to 0.107 watt of cooling at 4.5 K.

The minimum work required for the lead flow is also calculated from the changes of exergy from the supply and return flow conditions as shown in equation 7.

$$
\begin{array}{ll}
P_{in} = 5\ atm & P_{out} = 1\ atm \\
T_{in} = 4.5\ K & T_{out} = 305\ K \\
h_{in} = 12.11\ J/g & h_{out} = 1599\ J/g \\
s_{in} = 3.298\ J/g\text{-}K & s_{out} = 31.5\ J/g\text{-}K \\
E_{in} = 994\ J/g & E_{out} = 8009\ J/g
\end{array}
\tag{7}
$$

For each gram per second of flow rate, the minimum work required will be 7015 J/g. Thus 1 g/s of lead flow can be considered as (7015) / (66.8) = 105 watt at 4.5 K.

The Carnot efficiency is defined as the theoretical minimum work divided by the actual compressor work. In the present study, the shield heat load and the lead flow are converted into the equivalent 4.5 K heat load. The corresponding minimum work and the Carnot efficiency are then calculated. For RHIC, the 4.5 K load consists of heat load to the magnet, the power lead, the supply line and the return line. The total lead flow equals to $F_{74} + F_{76}$. The shield load is 55,000 watts. The equivalent heat load and the Carnot efficiency for the three cases under study are summarized in Table 1.

Table 1. Equivalent heat load and Carnot efficiency for RHIC Refrigerator

Case	4.5 K Load	Lead Flow	Equ. 4.5 K Load for Lead	Equ. 4.5 K Load for Shield	Total Equ. 4.5 K Load	Theoretical Minimum Work	Compressor Power	Carnot Efficiency
	watt	g/s	watt	watt	kilowatt	kilowatt	kilowatt	%
Baseline (60% Installed compressor)	5770	93	9765	~5900	21.4	1430	8803	16.2
"High Liquefaction" (full compressor)	14895	128	13440	~5900	34.2	2285	14182	16.1
"High Refrigeration" (full compressor)	18295	93	9765	~5900	34.0	2271	14165	16.0

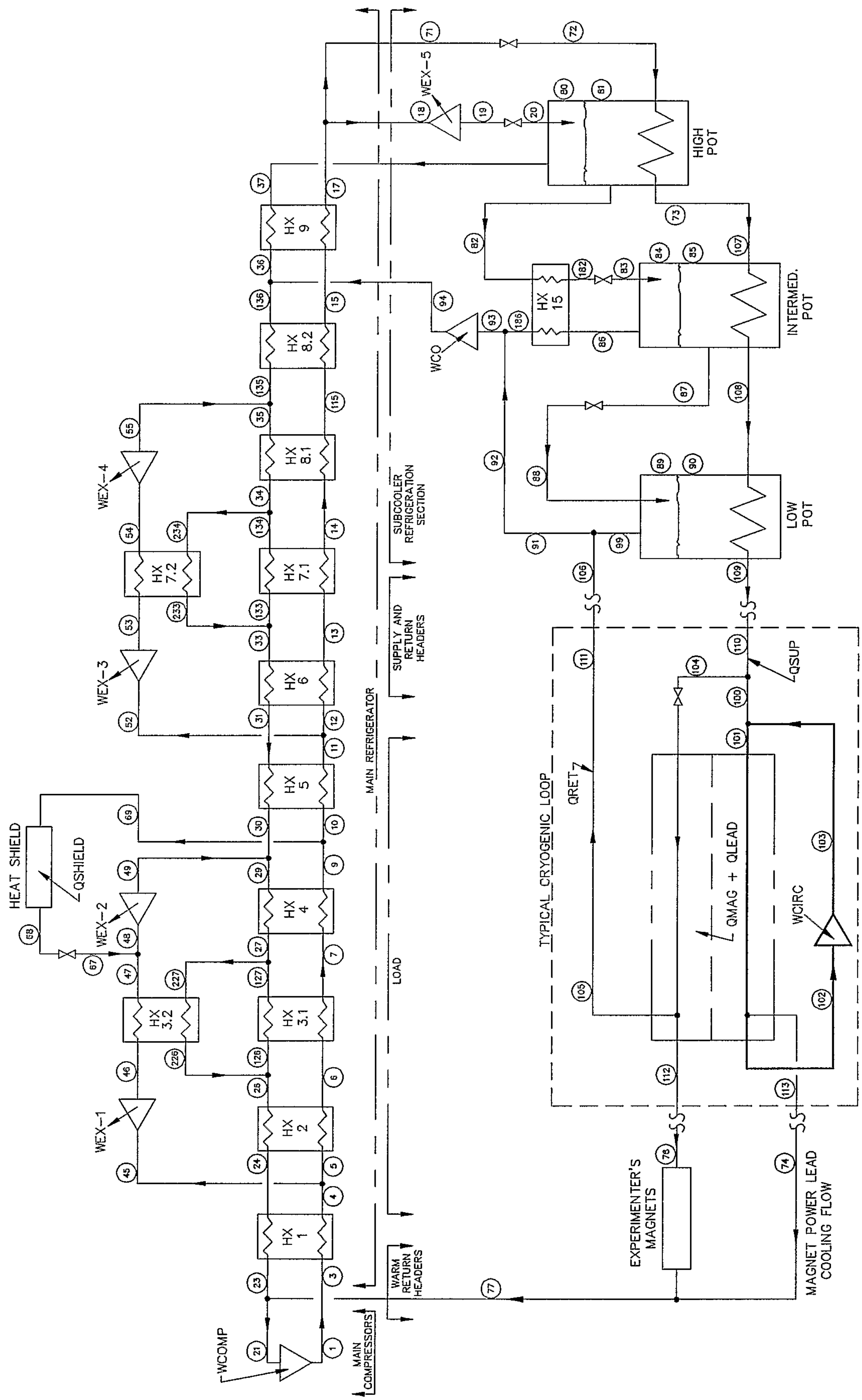

Fig. 1 Flow Diagram for RHIC Refrigerator

APPENDIX 1A: PROCESS REQUIREMENT FOR RHIC REFRIGERATOR AT DESIGN HEAT LOAD

FLUID PROPERTIES AND FLOW RATES

PRESSURE(ATM), TEMPERATURE(K), ENTHALPY(J/G) AND FLOW RATE(G/S)

PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S	PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S
1	17.25	305.00	1604.33	2486.45	3	16.40	305.00	1604.04	2486.45
4	16.28	180.00	954.62	2486.45	5	16.28	180.00	954.62	1853.27
6	16.18	151.78	807.86	1853.27	7	16.00	65.84	359.22	1853.27
9	15.68	40.00	222.00	1853.27	10	15.67	40.00	222.00	1448.95
11	15.64	25.00	139.41	1448.95	12	15.64	25.00	139.41	647.81
13	15.61	20.73	114.75	647.81	14	15.57	12.45	63.23	647.81
115	15.56	8.13	32.79	647.81	15	15.54	5.44	20.37	647.81
17	15.53	5.02	18.88	647.81	18	15.49	5.03	18.88	259.04
19	2.50	4.98	14.31	259.04	20	1.43	4.63	14.31	259.04
80	1.42	4.62	29.51	33.40	81	1.42	4.62	12.06	225.64
82	1.42	4.62	12.06	71.28	182	1.41	4.61	12.06	71.28
83	1.35	4.56	12.06	71.28	84	1.35	4.56	29.68	1.67
85	1.35	4.56	11.64	69.61	86	1.35	4.56	29.68	23.48
186	.92	4.13	29.68	23.48	87	1.35	4.56	11.64	47.80
88	.93	4.14	11.64	47.80	89	.93	4.14	30.15	5.31
90	.93	4.14	9.32	42.49	99	.93	4.14	30.15	47.80
91	.92	4.22	30.84	343.56	92	.92	4.21	30.84	343.56
93	.92	4.20	30.77	367.04	94	1.40	5.24	35.62	367.04
21	1.05	302.01	1583.34	2486.45	23	1.10	302.00	1583.34	2393.45
24	1.14	172.02	908.29	2393.45	26	1.17	149.88	793.30	2393.45
126	1.17	149.88	793.30	1783.57	127	1.24	60.00	326.38	1783.57
226	1.17	149.88	793.30	609.88	227	1.24	60.00	326.38	609.88
27	1.24	60.00	326.38	2393.45	29	1.29	39.42	219.34	2393.45
30	1.31	39.42	219.34	1355.95	31	1.32	22.50	130.91	1355.95
33	1.33	20.13	118.44	1355.95	133	1.33	20.13	118.44	626.21
134	1.35	10.06	64.67	626.21	233	1.33	20.13	118.44	729.75
234	1.35	10.06	64.67	729.75	34	1.35	10.06	64.67	1355.95
35	1.39	7.50	50.13	1355.95	135	1.39	7.50	50.13	554.81
136	1.40	5.24	35.62	554.81	36	1.40	5.24	35.62	187.77
37	1.41	4.62	29.51	187.77	45	16.23	180.00	954.62	633.18
46	9.00	151.78	805.66	633.18	47	8.90	65.84	358.03	633.18
48	8.86	65.84	358.03	1037.49	49	1.30	39.42	219.34	1037.49
52	15.58	25.00	139.41	801.15	53	8.00	20.73	118.09	801.15
54	7.92	12.45	69.49	801.15	55	1.41	7.50	50.13	801.15
67	8.90	65.84	358.03	404.32	68	9.67	65.81	358.03	404.32
69	15.67	40.00	222.00	404.32	71	15.49	5.03	18.88	388.77
72	5.13	5.76	18.88	388.77	73	5.03	4.67	12.82	388.77
74	4.58	4.50	11.94	48.00	76	.98	4.20	11.02	45.00
77	1.07	302.00	1583.33	93.00	100	5.00	6.56	27.69	24.00
101	5.00	5.21	15.50	124.00	102	4.58	4.50	11.94	100.00
103	5.00	4.62	12.57	100.00	104	5.01	4.19	11.02	170.38
105	.98	4.20	30.14	147.88	106	.93	4.23	30.95	295.77
107	5.03	4.67	12.82	388.77	108	5.02	4.61	12.55	388.77
109	5.01	4.19	11.02	388.77	110	5.01	4.19	11.02	194.38
111	.93	4.23	30.95	147.88	112	.98	4.20	11.02	22.50
113	4.58	4.50	11.94	24.00					

APPENDIX 1B: PERFORMANCE REQUIREMENT FOR RHIC REFRIGERATOR AT DESIGN HEAT LOAD

PROGRAM RHIC

CALCULATE PERFORMANCE OF RHIC HELIUM REFRIGERATOR WHICH UTILIZES 5 EXPANDERS AND 1 COLD VACUUM COMPRESSOR. CIRCULATING COMPRESSORS LOCATED IN THE RINGS ARE USED TO CIRCULATE THE COLD HELIUM THROUGH THE MAGNETS.

SUMMARY OF SYSTEM PARAMETERS

REFRIGERATION-WATTS					MASS FLOW-G/S	
QMAG	QLEAD	QSUP	QRET	QSHLD	F74	F76
2875.	1855.	800.	240.	55000.	48.	45.

ESTIMATED HEAT LEAKS IN THE HEAT EXCHANGERS - WATTS

HX1	HX2	HX3	HX4	HX5	HX6	HX7	HX8	HX9	H. POT	I. POT	L. POT
950.	3240.	2670.	1880.	240.	410.	600.	520.	180.	340.	290.	290.

HEAT EXCHANGER PARAMETERS

HEAT EXCHAN-GER	HIGH P FLOW G/S	LOW P FLOW G/S	CMAX/ CMIN	EFFECT-IVENESS RATIO	REQUIRED AU KW/K	REQUIRED NTU	DESIGN AU KW/K
1.0	2486.4	2393.4	1.040	.977	317.0	25.51	684.0
2.0	1853.3	2393.4	1.274	.937	64.2	6.66	183.1
3.1	1853.3	1783.6	1.046	.979	240.6	25.96	533.8
3.2	633.2	609.9	1.046	.979	81.3	25.66	103.8
4.0	1853.3	2393.4	1.256	.978	114.2	11.60	280.4
5.0	1449.0	1356.0	1.128	.967	94.9	13.40	201.2
6.0	647.8	1356.0	1.799	.873	12.7	3.38	58.4
7.1	647.8	626.2	1.216	.944	26.6	7.96	127.8
7.2	801.1	729.7	1.216	.944	31.0	7.95	148.5
8.1	647.8	1356.0	1.689	.895	13.9	3.05	33.7
8.2	647.8	554.8	1.191	.947	14.0	4.68	61.8
9.0	647.8	187.8	1.484	.807	3.1	1.69	11.5

EXPANDER PARAMETERS

TURBINE	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	ETA	WORK W
1.0	16.23	9.00	180.00	151.78	633.	.75	94317.
2.0	8.86	1.30	65.84	39.42	1037.	.75	143895.
3.0	15.58	8.00	25.00	20.73	801.	.70	17080.
4.0	7.92	1.41	12.45	7.50	801.	.70	15512.
5.0	15.49	2.50	5.03	4.98	259.	.50	1184.

COMPRESSOR PARAMETERS

COMP.	ISO-THER. EFF.	ADIA-BATIC EFF.	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	WORK KW	WORK H.P.	IN VOL FL ACFM	IN DENSI. G/CC	PRES RATIO
MAIN	.50		1.05	17.25	302.0	305.0	2486.	8803.	11801.			
COLD		.60	.92	1.40	4.20	5.24	367.0	1.779	2.385	52.4	.0148	1.531
CIRCU.		.50	4.58	5.00	4.50	4.62	100.0	.063	.084		.136	

ONE CIRCULATING COMPRESSOR IS REQUIRED IN EACH OF THE 2. CRYOGENIC LOOPS

LOAD SUMMARY

	PRIMARY LOAD SUPPLY	PRIMARY LOAD RETURN	SECONDARY LOAD SUPPLY	SECONDARY LOAD RETURN
FLOW RATE-G/S	388.77	295.77	404.32	404.32
PRESSURE-ATM	5.01	.93	15.67	9.67
TEMPERATURE-K	4.19	4.23	40.00	65.81
ENTHALPY-J/G	11.02	30.95	222.00	358.03

APPENDIX 2A: PROCESS REQUIREMENT FOR HIGH LIQUEFACTION CASE

FLUID PROPERTIES AND FLOW RATES

PRESSURE(ATM), TEMPERATURE(K), ENTHALPY(J/G) AND FLOW RATE(G/S)

PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S	PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S
1	17.25	305.00	1604.33	4000.86	3	16.40	305.00	1604.04	4000.86
4	16.28	180.00	954.62	4000.86	5	16.28	180.00	954.62	3102.73
6	16.18	153.31	815.81	3102.73	7	16.00	65.91	359.61	3102.73
9	15.68	40.00	222.00	3102.73	10	15.67	40.00	222.00	2699.56
11	15.64	25.00	139.41	2699.56	12	15.64	25.00	139.41	1393.74
13	15.61	20.52	113.46	1393.74	14	15.57	12.81	65.57	1393.74
115	15.56	8.30	33.77	1393.74	15	15.54	5.38	20.14	1393.74
17	15.53	5.00	18.78	1393.74	18	15.49	5.01	18.79	492.78
19	2.50	4.89	13.59	492.78	20	1.43	4.63	13.59	492.78
80	1.42	4.62	29.51	43.30	81	1.42	4.62	12.06	449.47
82	1.42	4.62	12.06	122.38	182	1.41	4.61	12.06	122.38
83	1.35	4.56	12.06	122.38	84	1.35	4.56	29.68	2.87
85	1.35	4.56	11.64	119.51	86	1.35	4.56	29.68	32.24
186	.92	4.13	29.68	32.24	87	1.35	4.56	11.64	90.14
88	.93	4.14	11.64	90.14	89	.93	4.14	30.15	10.01
90	.93	4.14	9.32	80.13	99	.93	4.14	30.15	90.14
91	.92	4.17	30.42	863.10	92	.92	4.16	30.42	863.10
93	.92	4.16	30.40	895.34	94	1.40	5.18	35.12	895.34
21	1.05	302.01	1583.34	4000.86	23	1.10	302.00	1583.34	3872.86
24	1.14	172.77	912.21	3872.86	26	1.17	151.20	800.16	3872.86
126	1.17	151.20	800.17	3003.40	127	1.24	60.39	328.43	3003.40
226	1.17	151.20	800.16	869.46	227	1.24	60.39	328.43	869.46
27	1.24	60.39	328.43	3872.86	29	1.29	39.11	217.70	3872.86
30	1.31	39.11	217.70	2571.56	31	1.32	22.50	130.91	2571.56
33	1.33	19.76	116.48	2571.56	133	1.33	19.76	116.48	1364.98
134	1.35	10.55	67.36	1364.98	233	1.33	19.76	116.48	1206.58
234	1.35	10.55	67.36	1206.58	34	1.35	10.55	67.36	2571.56
35	1.39	7.50	50.13	2571.56	135	1.39	7.50	50.13	1265.74
136	1.40	5.18	35.12	1265.74	36	1.40	5.18	35.12	370.40
37	1.41	4.62	29.51	370.40	45	16.23	180.00	954.62	898.13
46	9.00	153.31	813.61	898.13	47	8.90	65.91	358.42	898.13
48	8.86	65.91	358.42	1301.30	49	1.30	39.11	217.70	1301.30
52	15.58	25.00	139.41	1305.82	53	8.00	20.52	116.88	1305.82
54	7.92	12.81	71.72	1305.82	55	1.41	7.50	50.13	1305.82
67	8.90	65.91	358.42	403.17	68	9.67	65.89	358.42	403.17
69	15.67	40.00	222.00	403.17	71	15.49	5.00	18.78	900.97
72	5.13	5.75	18.78	900.97	73	5.03	4.67	12.82	900.97
74	4.58	4.50	11.94	48.00	76	.98	4.20	11.02	80.00
77	1.07	302.00	1583.33	128.00	100	5.00	6.56	27.69	24.00
101	5.00	5.21	15.50	124.00	102	4.58	4.50	11.94	100.00
103	5.00	4.62	12.57	100.00	104	5.01	4.19	11.02	426.48
105	.98	4.20	30.14	386.48	106	.93	4.18	30.45	772.97
107	5.03	4.67	12.82	900.97	108	5.02	4.61	12.55	900.97
109	5.01	4.19	11.02	900.97	110	5.01	4.19	11.02	450.48
111	.93	4.18	30.45	386.48	112	.98	4.20	11.02	40.00
113	4.58	4.50	11.94	24.00					

APPENDIX 2B: PERFORMANCE REQUIREMENT FOR HIGH LIQUEFACTION CASE

PROGRAM RHIC

CALCULATE PERFORMANCE OF RHIC HELIUM REFRIGERATOR WHICH UTILIZES 5 EXPANDERS AND 1 COLD VACUUM COMPRESSOR. CIRCULATING COMPRESSORS LOCATED IN THE RINGS ARE USED TO CIRCULATE THE COLD HELIUM THROUGH THE MAGNETS.

SUMMARY OF SYSTEM PARAMETERS

REFRIGERATION-WATTS					MASS FLOW-G/S	
QMAG	QLEAD	QSUP	QRET	QSHLD	F74	F76
12000.	1855.	800.	240.	55000.	48.	80.

ESTIMATED HEAT LEAKS IN THE HEAT EXCHANGERS - WATTS

HX1	HX2	HX3	HX4	HX5	HX6	HX7	HX8	HX9	H. POT	I. POT	L. POT
950.	3240.	2670.	1880.	240.	410.	600.	520.	180.	340.	290.	290.

HEAT EXCHANGER PARAMETERS

HEAT EXCHANGER	HIGH P FLOW G/S	LOW P FLOW G/S	CMAX/ CMIN	EFFECTIVENESS RATIO	REQUIRED AU KW/K	REQUIRED NTU	DESIGN AU KW/K
1.0	4000.9	3872.9	1.034	.977	540.3	26.86	684.0
2.0	3102.7	3872.9	1.237	.927	103.7	6.43	183.1
3.1	3102.7	3003.4	1.039	.977	405.9	26.02	533.8
3.2	898.1	869.5	1.039	.977	116.2	25.73	103.8
4.0	3102.7	3872.9	1.217	.966	171.5	10.41	280.4
5.0	2699.6	2571.6	1.107	.949	147.9	11.01	201.2
6.0	1393.7	2571.6	1.635	.852	25.5	3.16	58.4
7.1	1393.7	1365.0	1.194	.925	50.1	6.87	127.8
7.2	1305.8	1206.6	1.194	.925	44.1	6.85	148.5
8.1	1393.7	2571.6	1.478	.875	30.4	3.09	33.7
8.2	1393.7	1265.7	1.256	.951	30.2	4.64	61.8
9.0	1393.7	370.4	1.470	.790	6.3	1.73	11.5

EXPANDER PARAMETERS

TURBINE	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	ETA	WORK W
1.0	16.23	9.00	180.00	153.31	898.	.71	126649.
2.0	8.86	1.30	65.91	39.11	1301.	.76	183116.
3.0	15.58	8.00	25.00	20.52	1306.	.74	29431.
4.0	7.92	1.41	12.81	7.50	1306.	.75	28194.
5.0	15.49	2.50	5.01	4.89	493.	.57	2562.

COMPRESSOR PARAMETERS

COMP.	ISO-THER. EFF.	ADIA-BATIC EFF.	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	WORK KW	WORK H.P.	IN VOL FL ACFM	IN DENSI. G/CC	PRES RATIO
MAIN	.50		1.05	17.25	302.0	305.0	4001.	14165.	18988.			
COLD		.60	.92	1.40	4.16	5.18	895.3	4.234	5.676	124.8	.0152	1.531
CIRCU.		.50	4.58	5.00	4.50	4.62	100.0	.063	.084		.136	

ONE CIRCULATING COMPRESSOR IS REQUIRED IN EACH OF THE 2. CRYOGENIC LOOPS

LOAD SUMMARY

	PRIMARY LOAD SUPPLY	PRIMARY LOAD RETURN	SECONDARY LOAD SUPPLY	SECONDARY LOAD RETURN
FLOW RATE-G/S	900.97	772.97	403.17	403.17
PRESSURE-ATM	5.01	.93	15.67	9.67
TEMPERATURE-K	4.19	4.18	40.00	65.89
ENTHALPY-J/G	11.02	30.45	222.00	358.42

APPENDIX 3A: PROCESS REQUIREMENT FOR HIGH REFRIGERATION CASE

FLUID PROPERTIES AND FLOW RATES

PRESSURE(ATM), TEMPERATURE(K), ENTHALPY(J/G) AND FLOW RATE(G/S)

PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S	PT	PRES. ATM	TEMP. K	ENTHAL. J/G	FLOW G/S
1	17.25	305.00	1604.33	4005.65	3	16.40	305.00	1604.04	4005.65
4	16.28	180.00	954.62	4005.65	5	16.28	180.00	954.62	3333.14
6	16.18	151.40	805.88	3333.14	7	16.00	66.66	363.54	3333.14
9	15.68	40.00	222.00	3333.14	10	15.67	40.00	222.00	2941.21
11	15.64	25.00	139.41	2941.21	12	15.64	25.00	139.41	1603.80
13	15.61	20.46	113.14	1603.80	14	15.57	12.81	65.57	1603.80
115	15.56	8.38	34.31	1603.80	15	15.54	5.37	20.12	1603.80
17	15.53	5.00	18.76	1603.80	18	15.49	5.01	18.79	560.02
19	2.50	4.89	13.59	560.02	20	1.43	4.63	13.59	560.02
80	1.42	4.62	29.51	49.21	81	1.42	4.62	12.06	510.81
82	1.42	4.62	12.06	136.62	182	1.41	4.61	12.06	136.62
83	1.35	4.56	12.06	136.62	84	1.35	4.56	29.68	3.20
85	1.35	4.56	11.64	133.42	86	1.35	4.56	29.68	34.68
186	.92	4.13	29.68	34.68	87	1.35	4.56	11.64	101.94
88	.93	4.14	11.64	101.94	89	.93	4.14	30.15	11.32
90	.93	4.14	9.32	90.62	99	.93	4.14	30.15	101.94
91	.92	4.16	30.37	1052.71	92	.92	4.16	30.37	1052.71
93	.92	4.16	30.35	1087.40	94	1.40	5.17	35.06	1087.40
21	1.05	302.01	1583.34	4005.65	23	1.10	302.00	1583.34	3912.65
24	1.14	173.93	918.24	3912.65	26	1.17	149.37	790.70	3912.65
126	1.17	149.37	790.70	3255.02	127	1.24	62.10	337.34	3255.02
226	1.17	149.37	790.70	657.63	227	1.24	62.10	337.34	657.63
27	1.24	62.10	337.34	3912.65	29	1.29	38.84	216.28	3912.65
30	1.31	38.84	216.28	2848.21	31	1.32	22.50	130.91	2848.21
33	1.33	19.63	115.79	2848.21	133	1.33	19.63	115.79	1593.76
134	1.35	10.62	67.73	1593.76	233	1.33	19.63	115.79	1254.45
234	1.35	10.62	67.73	1254.45	34	1.35	10.62	67.73	2848.21
35	1.39	7.50	50.13	2848.21	135	1.39	7.50	50.13	1510.80
136	1.40	5.17	35.06	1510.80	36	1.40	5.17	35.06	423.40
37	1.41	4.62	29.51	423.40	45	16.23	180.00	954.62	672.50
46	9.00	151.40	803.68	672.50	47	8.90	66.66	362.33	672.50
48	8.86	66.66	362.33	1064.44	49	1.30	38.84	216.28	1064.44
52	15.58	25.00	139.41	1337.42	53	8.00	20.46	116.57	1337.42
54	7.92	12.81	71.72	1337.42	55	1.41	7.50	50.13	1337.42
67	8.90	66.66	362.33	391.93	68	9.67	66.63	362.33	391.93
69	15.67	40.00	222.00	391.93	71	15.49	5.00	18.76	1043.77
72	5.13	5.74	18.76	1043.77	73	5.03	4.67	12.82	1043.77
74	4.58	4.50	11.94	48.00	76	.98	4.20	11.02	45.00
77	1.07	302.00	1583.33	93.00	100	5.00	6.56	27.69	24.00
101	5.00	5.21	15.50	124.00	102	4.58	4.50	11.94	100.00
103	5.00	4.62	12.57	100.00	104	5.01	4.19	11.02	497.89
105	.98	4.20	30.14	475.39	106	.93	4.17	30.39	950.77
107	5.03	4.67	12.82	1043.77	108	5.02	4.61	12.55	1043.77
109	5.01	4.19	11.02	1043.77	110	5.01	4.19	11.02	521.89
111	.93	4.17	30.39	475.39	112	.98	4.20	11.02	22.50
113	4.58	4.50	11.94	24.00					

APPENDIX 3B: PERFORMANCE REQUIREMENT FOR HIGH REFRIGERATION CASE

PROGRAM RHIC

CALCULATE PERFORMANCE OF RHIC HELIUM REFRIGERATOR WHICH UTILIZES 5 EXPANDERS AND 1 COLD VACUUM COMPRESSOR. CIRCULATING COMPRESSORS LOCATED IN THE RINGS ARE USED TO CIRCULATE THE COLD HELIUM THROUGH THE MAGNETS.

SUMMARY OF SYSTEM PARAMETERS

REFRIGERATION-WATTS					MASS FLOW-G/S	
QMAG	QLEAD	QSUP	QRET	QSHLD	F74	F76
15400.	1855.	800.	240.	55000.	48.	45.

ESTIMATED HEAT LEAKS IN THE HEAT EXCHANGERS - WATTS

HX1	HX2	HX3	HX4	HX5	HX6	HX7	HX8	HX9	H. POT	I. POT	L. POT
950.	3240.	2670.	1880.	240.	410.	600.	520.	180.	340.	290.	290.

HEAT EXCHANGER PARAMETERS

HEAT EXCHAN-GER	HIGH P FLOW G/S	LOW P FLOW G/S	CMAX/ CMIN	EFFECT-IVENESS RATIO	REQUIRED AU KW/K	REQUIRED NTU	DESIGN AU KW/K
1.0	4005.6	3912.6	1.025	.977	597.4	29.40	684.0
2.0	3333.1	3912.6	1.165	.934	134.8	7.78	183.1
3.1	3333.1	3255.0	1.030	.977	481.5	28.47	533.8
3.2	672.5	657.6	1.030	.977	96.0	28.10	103.8
4.0	3333.1	3912.6	1.146	.957	193.8	10.95	280.4
5.0	2941.2	2848.2	1.089	.934	143.3	9.63	201.2
6.0	1603.8	2848.2	1.579	.841	28.5	3.06	58.4
7.1	1603.8	1593.8	1.177	.916	55.9	6.57	127.8
7.2	1337.4	1254.5	1.177	.916	43.8	6.55	148.5
8.1	1603.8	2848.2	1.418	.861	33.7	2.98	33.7
8.2	1603.8	1510.8	1.293	.953	34.3	4.54	61.8
9.0	1603.8	423.4	1.479	.788	7.2	1.74	11.5

EXPANDER PARAMETERS

TURBINE	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	ETA	WORK W
1.0	16.23	9.00	180.00	151.40	673.	.76	101511.
2.0	8.86	1.30	66.66	38.84	1064.	.78	155464.
3.0	15.58	8.00	25.00	20.46	1337.	.75	30550.
4.0	7.92	1.41	12.81	7.50	1337.	.75	28876.
5.0	15.49	2.50	5.01	4.89	560.	.57	2912.

COMPRESSOR PARAMETERS

COMP.	ISO-THER. EFF.	ADIA-BATIC EFF.	PIN ATM	POUT ATM	TIN K	TOUT K	FLOW G/S	WORK KW	WORK H.P.	IN VOL FL ACFM	IN DENSI. G/CC	PRES RATIO
MAIN	.50		1.05	17.25	302.0	305.0	4006.	14182.	19011.			
COLD		.60	.92	1.40	4.16	5.17	1087.4	5.127	6.873	151.1	.0153	1.531
CIRCU.		.50	4.58	5.00	4.50	4.62	100.0	.063	.084		.136	

ONE CIRCULATING COMPRESSOR IS REQUIRED IN EACH OF THE 2. CRYOGENIC LOOPS

LOAD SUMMARY

	PRIMARY LOAD SUPPLY	PRIMARY LOAD RETURN	SECONDARY LOAD SUPPLY	SECONDARY LOAD RETURN
FLOW RATE-G/S	1043.77	950.77	391.93	391.93
PRESSURE-ATM	5.01	.93	15.67	9.67
TEMPERATURE-K	4.19	4.17	40.00	66.63
ENTHALPY-J/G	11.02	30.39	222.00	362.33