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# CYCLE DESIGN FOR THE ISABELLE HELIUM REFRIGERATOR*

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## INTRODUCTION

The superconducting magnets for the ISABELLE storage ring/accelerator are designed to be operated at 3.8°K using a forced-flow supercritical helium cooling system.[1] The ISABELLE refrigerator has been designed subject to these special requirements. The design output is 13.65 KW of refrigeration below 4.2°K (for cooling the magnet and distribution system), 55 KW at 55°K (to cool heat shields for the whole system) and 100 g/s of liquefaction (for magnet power leads cooling). The system incorporates a subcooler section that produces liquid helium at 5.3 atm and 2.6K and circulates it through the loads, and a Claude-type main refrigerator section. The main refrigerator section has five stages of cooling, with four of them below liquid nitrogen temperature. Liquid nitrogen precooling is not used. With 60% isothermal compressors the efficiency of the refrigerator system will be about 26% of Carnot.

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## CYCLE OVERVIEW AND LOAD DESCRIPTION

The cycle schematic for the ISABELLE Refrigerator with a simplified load is given in Figure 1. The load and the subcooler section are connected by the supply and return headers. A circulating compressor in the subcooler section is used to pump helium through the headers and deliver cooling to the magnets. In addition, liquid helium is supplied for lead cooling and for cooling of the magnets in physics experiments set-up in the six intersection regions of ISABELLE. Hence, the load is a combination of refrigeration and liquefaction.

The nominal operating pressure for the ISABELLE load has been chosen[1] as 5 atm. This will be the minimum pressure permitted. Higher pressures will be allowed during cooldown and other periods of high heat loads when the temperature of the system rises above the design level. The control system will be set to maintain essentially constant helium density at the inlet to the circulating compressor. Minor adjustments in the rotational speed of the circulating compressor will then be used to trim for constant flow rate to the load. This method of operation is intended to reduce the need for venting of helium and subsequent "reliquefaction."

Based on theoretical and experimental results, the loads for four possible conditions have been estimated. The performance requirements in terms of forced flow are described in Table 1. For the base design mode, the refrigeration is 13.7 KW and the liquefaction rate is 100 g/s. The heat shield load is 55 KW, provided by 350 g/s of helium flowing between 40°K and 70°K, for all conditions.

Table 1: Performance Requirements for ISABELLE Refrigerator

| Mode of Operation | Supply Condition | | | Return Condition | | | Refrig. Effect | Liquid He Produced |
|---|---|---|---|---|---|---|---|---|
| | Flow (g/s) | Press. (atm) | Temp. (°K) | Flow (g/s) | Press. (atm) | Temp. (°K) | (KW) | (g/s) |
| Base Design | 4156 | 5.35 | 2.59 | 4054 | 4.20 | 4.19 | 13.7 | 100 |
| High Refrigeration | 4462 | 5.35 | 2.59 | 4379 | 4.20 | 4.16 | 14.4 | 86 |
| High Liquefaction | 3022 | 5.35 | 2.59 | 2878 | 4.20 | 4.31 | 11.1 | 144 |
| 4.3°K Magnet Temp. | 3959 | 6.35 | 2.98 | 3859 | 5.20 | 4.64 | 16.2 | 100 |

## SUBCOOLER SECTION

The subcooler section of the refrigerator, shown in the lower half of Figure 1, incorporates some unique features. It consists of cold vacuum compressors, a circulating compressor and heat exchangers/pots. The vacuum compressors are designed to pump the intermediate pot to 0.35 atm (3.2°K) and the low pot to 0.1 atm (2.5°K). Cold vacuum compressors were selected rather than using a subatmospheric suction in the main warm compressor, to minimize system power input, to avoid the risk of leaking air into the system, and to reduce the cross section area of the heat exchangers. The circulating compressor pumps approximately 4,000 g/s of helium through the load. This is several times the flow rate that could be provided by the cold end of the refrigerator and is comparable to the main compressor flow.

A performance summary for the cold compressors at base design mode is given as part of Figure 2. These three units contribute approximately 10 KW heat load at 4.5°K and 20 KW between 4.6°K and 9°K. As a result, the ISABELLE refrigerator must generate substantial amounts of refrigeration between 4.5°K and 10°K in order to satisfy the requirement to operate below 4.2°K.

The addition of heat exchanger HX-15 between the high pot and the intermediate pot has been found to increase the plant efficiency by approximately 5%.

## MAIN REFRIGERATOR

The ISABELLE refrigerator uses a Claude-type cycle. Because of its large capacity, features have been incorporated that are not customary in smaller refrigerators.

The efficiency of a helium refrigerator increases with the number of expanders and has been reported to level off at five.[2,3] Numerical studies of three and five expander cycles were performed as part of the studies leading to the ISABELLE cycle. These verified the economical advantages of using the five expander cycle which has been selected (see Figure 1).

Expansion stages 1 and 2 and stages 3 and 4 are connected in series between the high and low pressure streams. The series arrangement allows a higher flow rate across a lower expansion ratio for each turboexpander, as compared to individual units arranged in parallel, and makes possible higher turbine efficiencies.[4]

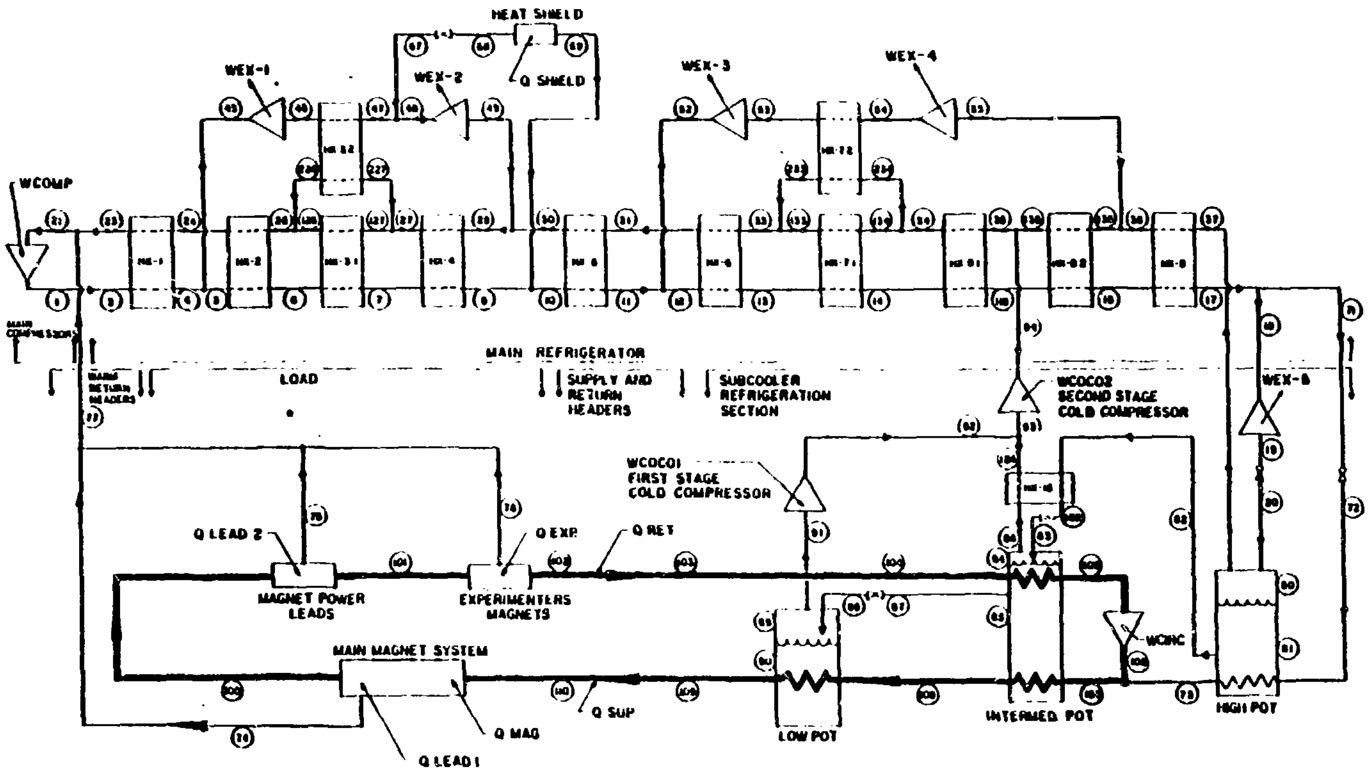


Fig. 1 Cycle schematic for ISABELLE refrigerator.

PROGRAM ISA62

CALCULATED PERFORMANCE OF A HELIUM REFRIGERATOR WHICH UTILIZES 5 EXPANDERS AND 3 COLD COMPRESSORS. DELIVERY OF THE REFRIGERANT IS IN THE FORM OF COMPRESSED LIQUID HELIUM WHICH IS CIRCULATED BY ONE OF THE THREE COMPRESSORS IN THE CYCLE.

SUMMARY OF SYSTEM PARAMETERS

SYSTEM DESIGN STEADY-STATE LOAD REQUIREMENTS

| REFRIGERATION REQUIRED-WATTS | | | | | | | MASS FLOW REQUIRED-GM/SEC | | |
|---|---|---|---|---|---|---|---|---|---|
| QMAG | QLEAD1 | QLEAD2 | QSUP | QRET | QEXP | QSHLD | F74 | F75 | F78 |
| 7650. | 200. | 2300. | 1500. | 2000. | 0. | 55000. | 6. | 44. | 58. |

OTHER ESTIMATED REFRIGERATION LOADS-WATTS

| QHX1 | QHX2 | QHX3 | QHX4 | QHX5 | QHX6 | QHX7 | QHX8 | QHX9 | QHX10 | QHX11 | QHX12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3600.0 | 1200.0 | 2400.0 | 800.0 | 600.0 | 500.0 | 500.0 | 200.0 | 150.0 | 100.0 | 100.0 | 100.0 |

EXPANDER/COMPRESSOR PARAMETERS

| | MAIN COMPR. | COLD COMPR 1 | COLD COMPR 2 | CIRC. COMPR. | EXPANDER 1 | EXPANDER 2 | EXPANDER 3 | EXPANDER 4 | EXPANDER 5 |
|---|---|---|---|---|---|---|---|---|---|
| ADIABATIC EFFICIENCY | | .730 | .730 | .620 | .810 | .820 | .800 | .780 | .760 |
| ISOTHERMAL EFFICIENCY | .60 | | | | | | | | |
| INLET PRESSURE-ATM | 1.050 | .095 | .340 | 4.150 | 16.227 | 8.860 | 15.579 | 7.922 | 15.494 |
| OUTLET PRESSURE-ATM | 17.250 | .350 | 1.389 | 5.450 | 9.000 | 1.301 | 8.000 | 1.423 | 2.600 |
| INLET TEMPERATURE-K | 302.00 | 2.46 | 4.56 | 3.47 | 185.00 | 69.48 | 25.00 | 12.38 | 8.28 |
| OUTLET TEMPERATURE-K | 305.00 | 4.69 | 9.18 | 3.76 | 153.64 | 38.08 | 20.18 | 7.10 | 5.14 |
| FLOW RATE-GM/SEC | 3997.5 | 324.0 | 945.9 | 4054.0 | 648.3 | 1002.9 | 1590.4 | 1590.4 | 1304.2 |
| WORK-WATTS | 11794440. | 3562. | 21637. | 5812. | -107172. | -160487. | -38752. | -33790. | [illegible] |
| WORK-HP | 15810. | 5. | 29. | 8. | -144. | -215. | -52. | -45. | -13. |

HEAT EXCHANGER EFFECTIVENESS RATIO

| HX1 | HX2 | HX3.1 | HX3.2 | HX4 | HX5 | HX6 | HX7.1 | HX7.2 | HX8.1 | HX9 |
|---|---|---|---|---|---|---|---|---|---|---|
| .976 | .940 | 978 | 978 | .966 | 942 | .960 | 980 | .980 | 783 | .948 |

| HX8.2 | HX15 |
|---|---|
| .950 | .928 |

LOAD SUMMARY

| | PRIMARY LOAD | | SECONDARY LOAD | |
|---|---|---|---|---|
| | SUPPLY | RETURN | SUPPLY | RETURN |
| FLOW RATE-GM/SEC | 4153.98 | 4053.98 | 354.61 | 354.61 |
| TEMPERATURE-K | 2.59 | 4.19 | 40.00 | 69.45 |
| PRESSURE-ATM | 5.35 | 4.20 | 15.67 | 9.67 |
| DENSITY-GM/CC | .154 | .139 | .01042 | .00666 |
| ENTHALPY-J/GM | 7.32 | 10.63 | 222.00 | 377.10 |

Fig. 2. Summary on the performances requirements of ISABELLE refrigerator

No liquid nitrogen precooling is used because the system is primarily a refrigerator (as opposed to a liquefier). This is due to the extra load from compressors power input in the subcooler section. The use of the warm expansion stage to substitute for liquid nitrogen precooling can also be justified on the basis of economic and operational considerations.

The heat shield circuit parallels heat exchanger 4 and expansion stage 2, with the return helium from the circuit providing about 35% of the flow into the expander.

## DETAIL DESIGN

With loads and cycle configuration defined, the state variables at each process point can be determined from basic thermodynamic relationships. Iteration is required until component efficiencies, pressure drops and heat leaks are consistent with the hardware design. A computer program utilizing the NBS helium properties[5] was developed by BNL to accomplish the necessary computations. The program first calculates the circulating flow requirement for a given load, and the cooling required at the three pots in the subcooler. The interface condition between subcooler and refrigerator is then obtained from vacuum compressor performance projections. Finally the sizing of turbines and heat exchangers for the refrigerator are performed. A typical summary describing the load conditions, performance requirement of turbines, compressors and heat exchangers, and the state at each process point is in given Figures 2 and 3.

At base design condition, the pressure in the low pot of the subcooler is chosen to be 0.1 atm corresponding to 2.49°K. This is the lowest temperature in the system. The pressure in the intermediate pot is chosen to be 0.35 atm, corresponding to 3.27°K.

The inlet temperatures for the expansion stages have been chosen to optimize the cycle, given the load and subcooler section requirements. All expansion stages but the first are below liquid nitrogen temperature. The outlet pressure of expander 5 is set at 2.5 atm to avoid liquid formation, although in practice, this may not be necessary. The total power extraction from the expansion stages is around 350 KW. The turboexpanders all have variable inlet nozzles to permit achieving near optimum efficiency over a wide flow rate range. This is particularly important during cooldown.

High effectiveness heat exchangers are used. Temperature differences across heat exchangers have been adjusted so that most of heat exchangers have effectiveness higher than 0.94, but

FLUID PROPERTIES AND FLOW RATES

PRESSURE(ATM), TEMPERATURE(K), ENTHALPY(J/GM) AND FLOW RATE(GM/SEC)

| POINT | PRESS. | TEMP. | ENTHAL. | FLOW |
|---|---|---|---|---|
| 1 | 17.250 | 305.00 | 1604.33 | 3997.48 |
| 3 | 16.400 | 305.00 | 1604.04 | 3997.48 |
| 4 | 16.278 | 185.00 | 980.61 | 3997.48 |
| 5 | 16.278 | 185.00 | 980.61 | 3349.15 |
| 6 | 16.181 | 153.64 | 817.52 | 3349.15 |
| 7 | 15.899 | 69.48 | 378.39 | 3349.15 |
| 9 | 15.676 | 40.00 | 222.00 | 3349.15 |
| 10 | 15.666 | 40.00 | 222.00 | 2994.54 |
| 11 | 15.636 | 25.00 | 139.41 | 2994.54 |
| 12 | 15.636 | 25.00 | 139.41 | 1404.15 |
| 13 | 15.606 | 20.19 | 111.54 | 1404.15 |
| 14 | 15.575 | 12.38 | 62.75 | 1404.15 |
| 115 | 15.558 | 9.88 | 44.58 | 1404.15 |
| 15 | 15.543 | 7.28 | 28.14 | 1404.15 |
| 17 | 15.533 | 6.28 | 23.69 | 1404.15 |
| 18 | 15.494 | 6.29 | 23.59 | 1304.15 |
| 19 | 2.500 | 5.14 | 15.93 | 1304.15 |
| 20 | 1.434 | 4.61 | 15.83 | 1304.15 |
| LIQUID FRACTION AT PT. 20 IS .778 | | | | |
| 80 | 1.424 | 4.61 | 29.54 | 358.27 |
| 81 | 1.424 | 4.61 | 11.99 | 1011.12 |
| 82 | 1.424 | 4.61 | 11.99 | 945.88 |
| 182 | 1.414 | 3.47 | 7.07 | 945.88 |
| 83 | .350 | 3.27 | 7.07 | 945.88 |
| LIQUID FRACTION AT PT. 83 IS .953 | | | | |
| 84 | .350 | 3.27 | 29.03 | 621.86 |
| 85 | .350 | 3.27 | 5.99 | 901.56 |
| 86 | .350 | 3.27 | 29.03 | 621.86 |
| 186 | .340 | 4.50 | 36.51 | 621.86 |
| 87 | .350 | 3.27 | 5.99 | 324.02 |
| 88 | .100 | 2.49 | 5.99 | 324.02 |
| LIQUID FRACTION AT PT. 88 IS .913 | | | | |
| 89 | .100 | 2.49 | 26.63 | 324.02 |
| 90 | .100 | 2.49 | 4.02 | 295.75 |
| 91 | .095 | 2.46 | 26.53 | 324.02 |
| 92 | .350 | 4.69 | 37.52 | 324.02 |
| 93 | .340 | 4.56 | 36.86 | 945.88 |
| 94 | 1.309 | 9.18 | 59.73 | 945.88 |

| POINT | PRESS. | TEMP. | ENTHAL. | FLOW |
|---|---|---|---|---|
| 21 | 1.050 | 302.00 | 1583.34 | 3997.48 |
| 23 | 1.100 | 302.00 | 1583.34 | 3897.48 |
| 24 | 1.139 | 178.69 | 942.99 | 3897.48 |
| 26 | 1.166 | 151.65 | 802.53 | 3897.48 |
| 126 | 1.166 | 151.65 | 802.53 | 3264.68 |
| 127 | 1.243 | 64.86 | 351.68 | 3264.68 |
| 226 | 1.166 | 151.65 | 802.53 | 632.80 |
| 227 | 1.243 | 64.86 | 351.68 | 632.80 |
| 27 | 1.243 | 64.86 | 351.68 | 3897.48 |
| 29 | 1.284 | 38.99 | 217.08 | 3897.48 |
| 30 | 1.306 | 38.99 | 217.08 | 2894.54 |
| 31 | 1.318 | 22.60 | 131.43 | 2894.54 |
| 33 | 1.330 | 20.00 | 117.74 | 2894.54 |
| 133 | 1.330 | 20.00 | 117.74 | 1399.63 |
| 134 | 1.348 | 10.78 | 68.61 | 1399.63 |
| 233 | 1.330 | 20.00 | 117.74 | 1494.92 |
| 234 | 1.348 | 10.78 | 68.61 | 1494.92 |
| 34 | 1.348 | 10.78 | 68.61 | 2894.54 |
| 35 | 1.389 | 9.18 | 59.73 | 2894.54 |
| 135 | 1.389 | 9.18 | 59.73 | 1948.66 |
| 136 | 1.404 | 7.10 | 47.78 | 1948.66 |
| 36 | 1.404 | 7.10 | 47.78 | 358.27 |
| 37 | 1.411 | 4.60 | 29.54 | 358.27 |
| 100 | 4.550 | 3.80 | 9.57 | 4147.98 |
| 101 | 4.550 | 3.99 | 10.13 | 4103.98 |
| 102 | 4.550 | 3.99 | 10.13 | 4053.98 |
| 103 | 4.200 | 4.19 | 10.63 | 4053.98 |
| 104 | 4.200 | 4.19 | 10.63 | 4053.98 |
| 105 | 4.150 | 3.47 | 8.47 | 4053.98 |
| 106 | 5.450 | 3.76 | 9.91 | 4053.98 |
| 107 | 5.450 | 3.78 | 9.99 | 4153.98 |
| 108 | 5.400 | 3.37 | 8.81 | 4153.98 |
| 109 | 5.350 | 2.59 | 7.32 | 4153.98 |
| 110 | 5.000 | 2.90 | 7.68 | 4153.98 |

| POINT | PRESS. | TEMP. | ENTHAL. | FLOW |
|---|---|---|---|---|
| 45 | 16.227 | 185.00 | 980.61 | 648.33 |
| 46 | 9.000 | 153.64 | 815.31 | 648.33 |
| 47 | 8.904 | 69.48 | 377.10 | 648.33 |
| 48 | 8.860 | 69.48 | 377.10 | 1002.94 |
| 49 | 1.301 | 38.99 | 217.08 | 1002.94 |
| 52 | 15.579 | 25.00 | 138.41 | 1590.39 |
| 53 | 8.000 | 20.19 | 116.05 | 1590.39 |
| 54 | 7.922 | 12.38 | 60.03 | 1590.38 |
| 55 | 1.423 | 7.10 | 47.78 | 1590.39 |
| 67 | 8.904 | 69.48 | 377.10 | 354.61 |
| 68 | 8.666 | 69.45 | 377.10 | 354.61 |
| 69 | 15.666 | 40.00 | 222.00 | 354.61 |
| 71 | 15.494 | 6.29 | 23.59 | 100.00 |
| 72 | 5.550 | 6.34 | 23.59 | 100.00 |
| 73 | 5.450 | 4.71 | 13.14 | 100.00 |
| 74 | 4.975 | 3.35 | 8.63 | 6.00 |
| 75 | 4.550 | 3.80 | 9.67 | 44.00 |
| 76 | 4.550 | 3.99 | 10.13 | 50.00 |
| 77 | 1.050 | 302.00 | 1583.32 | 100.00 |

Fig. 3. State variables at each process point in the ISABELLE cycle.

none exceed 0.98. The total UA for heat exchangers is about 2100 KW/°K.

The high and low pressure streams in the refrigerator are at 16.4 atm and 1.1 atm. The mid pressure between series-connected expansion stages is about 8 atm. The choice of 1.1 atm as the lowest pressure is to avoid subatmospheric suction in the main compressors. No significant cycle improvements were observed for high pressures greater than 16.4 atm. The total compressor flow required is about 4,000 g/s. It is estimated that 12 MW to 15 MW of input power will be required depending on the efficiency of the compressors which are used.

## REMARKS

In order to enhance the reliability and flexibility of this plant, redundant heat exchangers (1-2) and expanders, (1, 2, 3 and 4) will be provided. The redundant expanders 1 and 2 serve in a way similar to liquid nitrogen precooling to increase the cooling capacity of the system significantly during cooldown. An analysis of the cooldown process is given in Ref. 6. With redundant expanders 1 and 2 operating, the ISABELLE plant can be operated as a liquefier which will be capable of producing 11,000 l/hr liquid helium at 4.6°K.

The refrigerator is now under construction and is scheduled for completion and testing in 1983.

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