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LABORATORY TESTING OF A SUPERCRITICAL HELIUM PUMP FOR A MAGNETIC REFRIGERATOR

N3953618

Prepared By:	Pao-lien Wang
Academic Rank:	Associate Professor
University and Department:	University of North Carolina at Charlotte Engineering Technology
NASA/KSC:	
Division:	Mechanical Engineering
Branch:	Special Projects
NASA Counterpart:	Frank Howard
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ABSTRACT

A supercritical helium pump testing system for a magnetic refrigerator has been built. Details of the supercritical helium pump, the test system, and the test instrumentation are given in this report. Actual pump tests were not run during this ASEE term because of delivery problems associated with the required pump flow meter. Consequently, efforts were directed on preliminary design of the magnetic refrigeration system for the pump.

The first concern with the magnetic refrigerator preliminary design was determining how to effectively use the pump in the magnetic refrigerator. A method to incorperate the supercritical helium pump into a magnetic refrigerator was determined by using a computer model. An illustrated example of this procedure is given to provide a tool for sizing the magnetic refrigerator system as a function of the pump size.

The function of the computer model and its operation are also outlined and discussed.

1 INTRODUCTION

Kennedy Space Center is in the process of developing a highly efficient cryogenic refrigerator to be used to reliquify the liqid hydrogen boil-off. At the present, the boil-off hydrogen is vented and the replacement cost is very high. If the boil-off hydrogen can be sucessfully reliquified, the savings would be substantial. In addition, there is a possibility that this refrigerator can be used for air conditioning.

The common practice for liquefaction of gases is accomplished by refrigeration method in which gases such as hydrogen gas is compressed in one part of the refrigeration cycle with heat rejected from the gas, then expanded in another part of the cycle to cool and liquefy a portion of the gas. The major disadvantages of the refrigeration method are: (a) low efficiency, (b) large size and (c) large mass. In order to overcome these disadvantages, a system that offers higher efficiency, small size and lower mass is needed. The development of a magnetic refrigeration cycle may offer these advantages.

2 PURPOSE

The purpose of this project was to develop a high efficiency magnetic refrigerator by:

(a) Setup a supercritical helium pump testing system to determine the performance of the pump,
(b) Determining a best method to incorperate the pump into a magnetic refirgeration system by using a computer simulation model.

3 PUMP TESTING PROGRAM

3.1 TEST SYSTEM. The testing system was setup by the Boeing Aerospace Operation. It consists of a supercritical helium pump, a supply tank, inlet and outlet pressure transducers, inlet and outlet temperature sensors, a flow meter, a heat exchanger, a pump speed control device, and associated required plumbing. A schematic diagram and a photograph of the facility are shown in Fig. 3.1 and Fig. 3.2 respectively. For cost reduction, the pump was determined to be tested

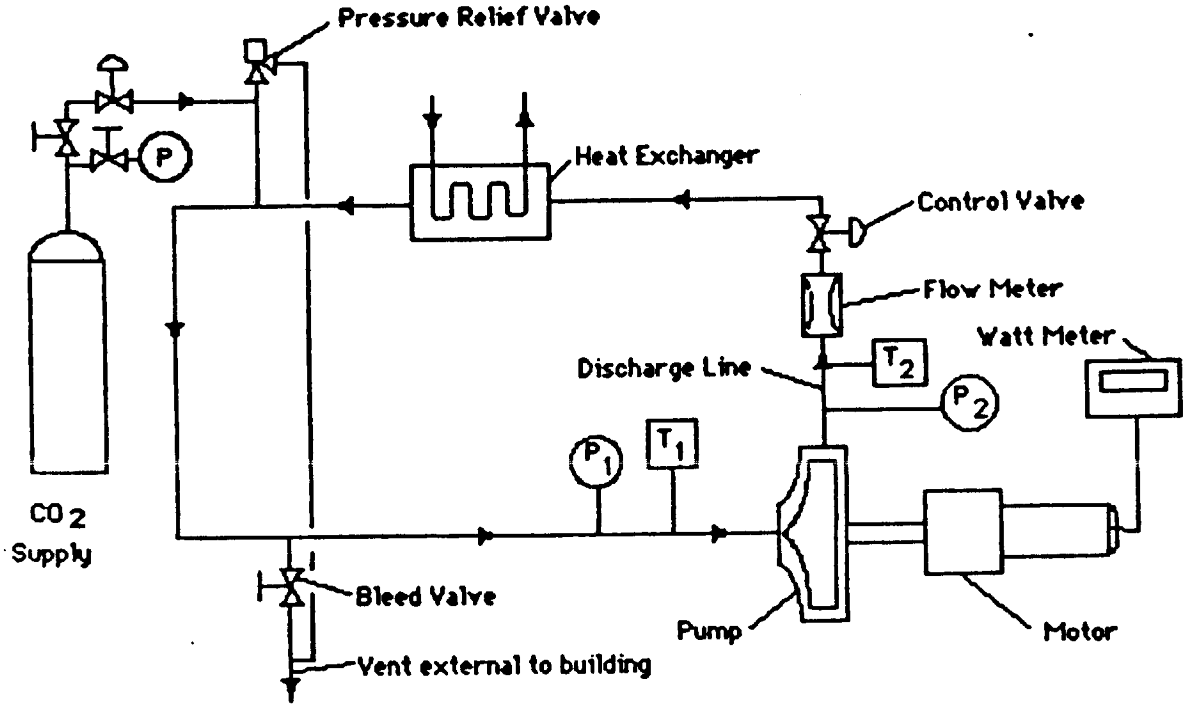

Figure 3.1. Schematic of Pump Test System

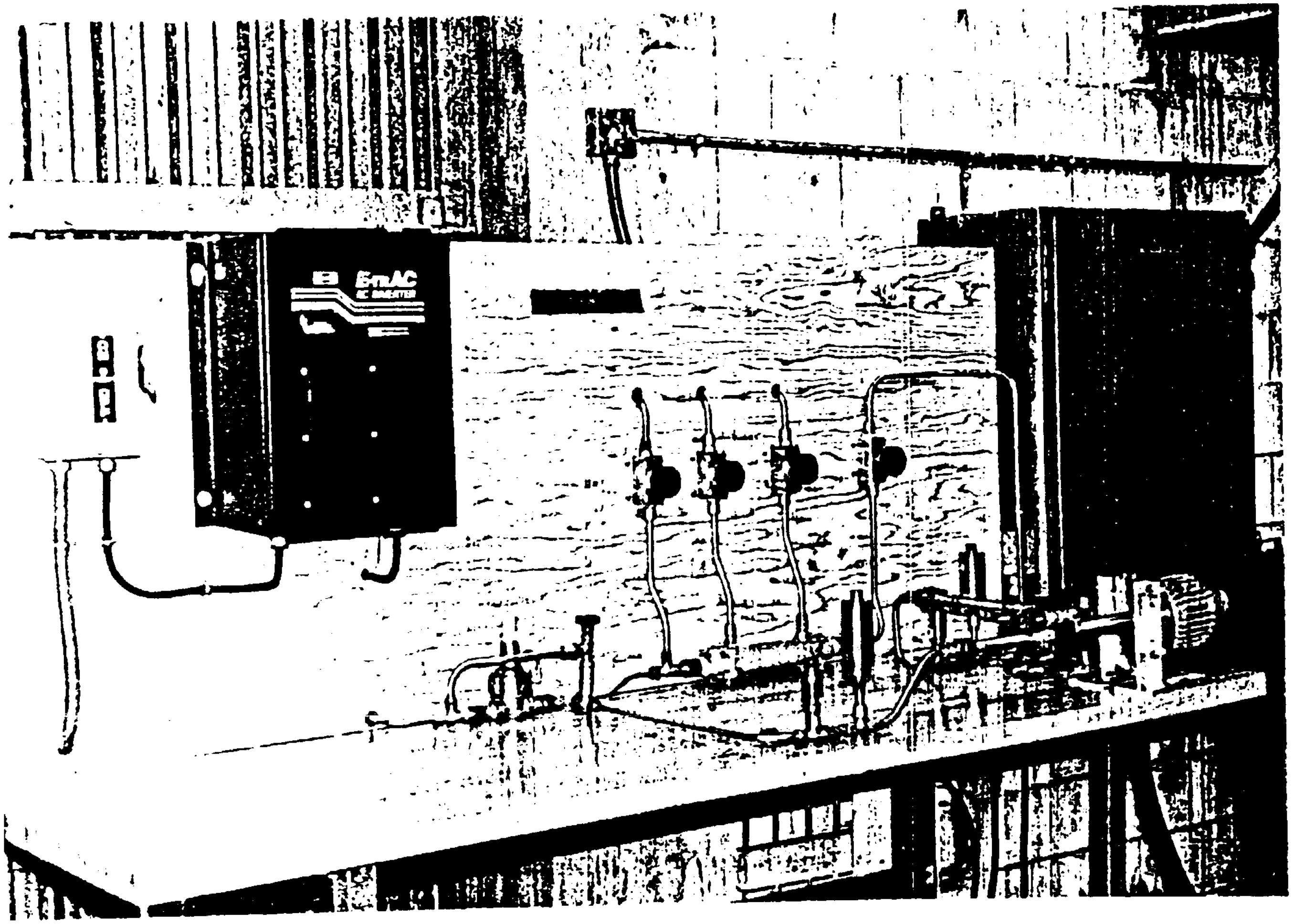

Figure 3.2. Pump Test Facility

with carbon dioxide instead of supercritical helium.

3.1.1 The Supercritical Helium Pump. A cross-section and a photograph of the pump are shown in Fig. 3.3 and Fig. 3.4. The pump was manufactured by Barber-Nichols Engineering Company of Arvada, Colorado (Model BNHeP-04-001). The pump is a partial emission centrifugal pump running at 12,500 rpm. The specific speed of 33 allows the device to operate at 61% efficiency at the design inlet condition of 20K, five atmospheres pressure and 4800 cc/sec. flow rate. The inlet power to the pump is 0.24 Kw at the design differential head of 0.35 atmospheres. This pump is designed to minimize heat leak to ambient and to the pumped fluid allowing the motor to be placed outside the refrigerator with a long 304 stainless steel support tube and drive shaft to separate the pump from ambient conditions to lower conduction and convection losses. The shaft is evacuated and electron-beam seal welded to eliminate internal convective losses. The motor drive is a high efficiency, two-pole, 3 phase, 208 V induction motor designed to operate at 220 Hz frequency. The motor is driven by a modified commercial frequency inverter to take single-phase, 220 V, 60 Hz input and give variable speed up to and beyond 220 Hz (12,500 rpm). The motor end of the drive shaft is supported on a rotating disc-type coupling to allow for slight angular movement of the pump shaft during cool-down without increasing bearing loads.

3.1.2 Instrumentation. The instrument used in this system are listed as follows:

- Inlet temperature sensor
  - Scientific Instruments Inc.
  - Model #X49WT-04-04
  - S.N. 876W
  - Range +50F to +122F
- Outlet temperature sensor
  - Scientific Instruments Inc.
  - Model #X49WT-04-04
  - S.N. 875W
  - Range +50F to +122F
- Inlet pressure transducer
  - Teledyne Taher
  - Model 2403
  - S.N. 844340
  - Range 0 to 150 psig

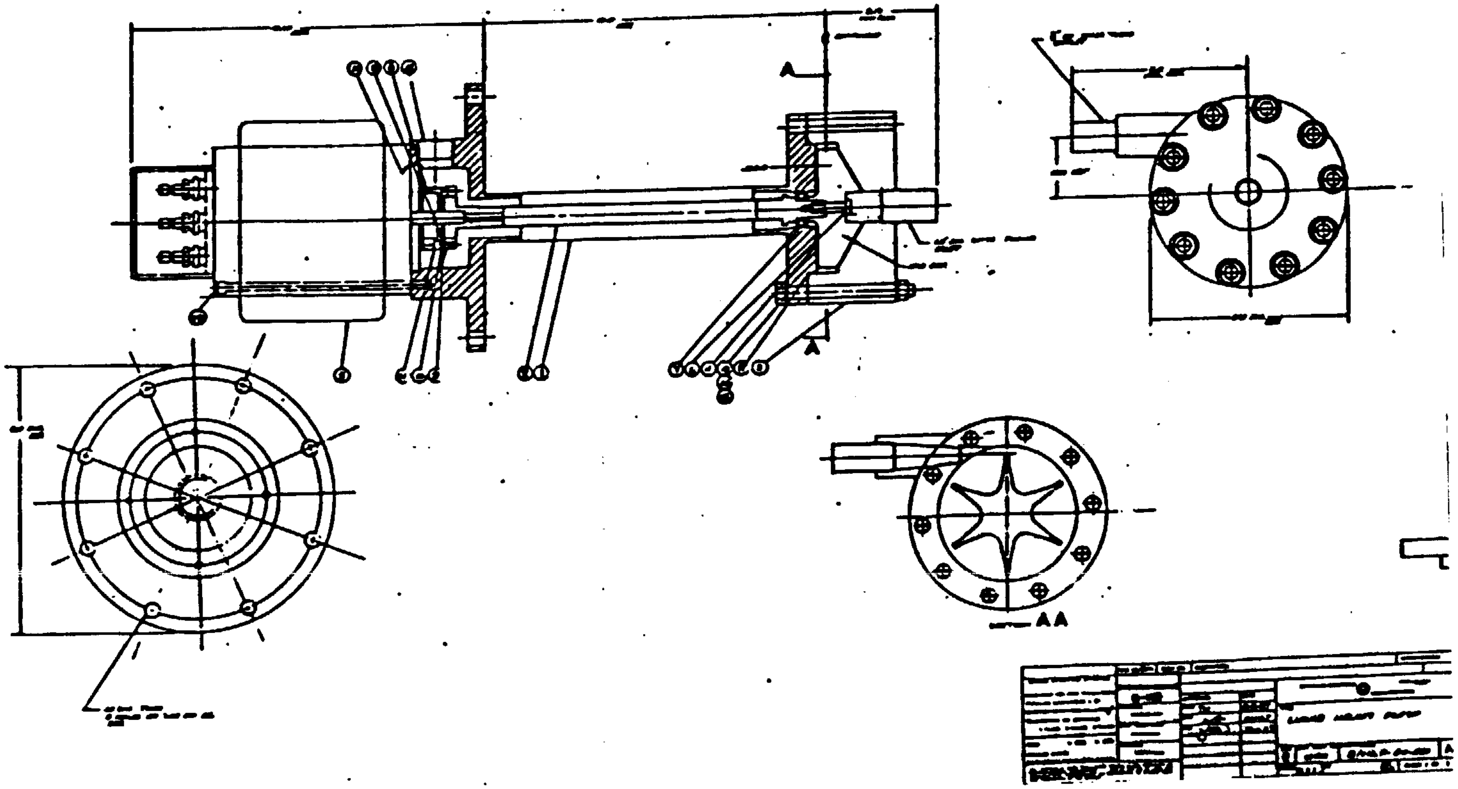

Figure 3.3. Cross-section of Supercritical Helium Pump

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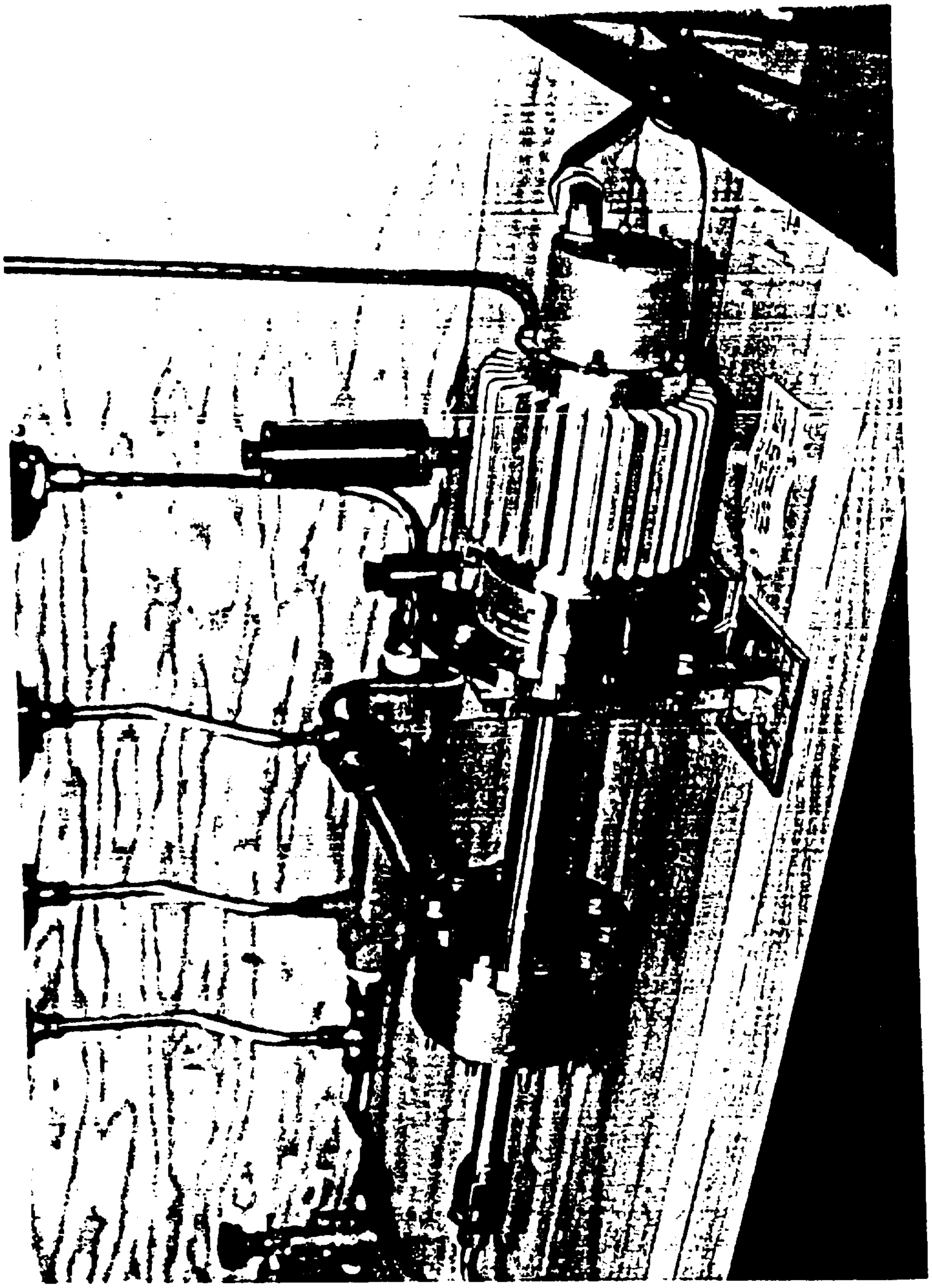

Figure 3.4. Photograph of Supercritical Helium Pump

Outlet pressure transducer
    Teledyne Taher
    Model 2403
    S.N. 834241
    Range 0 to 150 psig
Flow meter
    Wallace and Tiernan
    Straight-through Varea Meter
    P.N. TEF5223AT7012XABC40VTX
    Presssure: 75 psig
    Temperature: 50 - 90F
    Flow: 15 to 60 SCFM
Accuracy: +/- 2% of full scale
Heat exchanger
    Foam Heater
    Young Radiator Co.
    Part #262140
Motor speed control
    T.B. Woods Sons Co.
    E-TrAC
    AC Inverter

3.1.3 Test Procedures. Has been documented by the author in the 1987 NASA/ASEE Summer Fellowship final report. (see reference 1)

3.1.4 Test Results. The pump will be tested by the Boeing Aerospace Operation Contractor. Due to the absence of flow meter (ordered but not delivered at the time of this writing) test can not be performed.

4 THE MAGNETIC REFRIGERATOR

4.1 FUNDAMENTAL CONCEPTS. The magnetic refrigerator uses a paramagnetic material as the refrigerant. Its operation is based on the natural phenomenon that paramagnetic materials become warmer when they are subjected to a magnetic field and cooler when the magnetic field is removed. A schematic of a recuperative magnetic refrigerator (possible KSC model) is shown in Fig. 4.1. It is a rotational device where the rim of wheel is composed of magnetic working material plates (or packed bed particles). A fluid (such as

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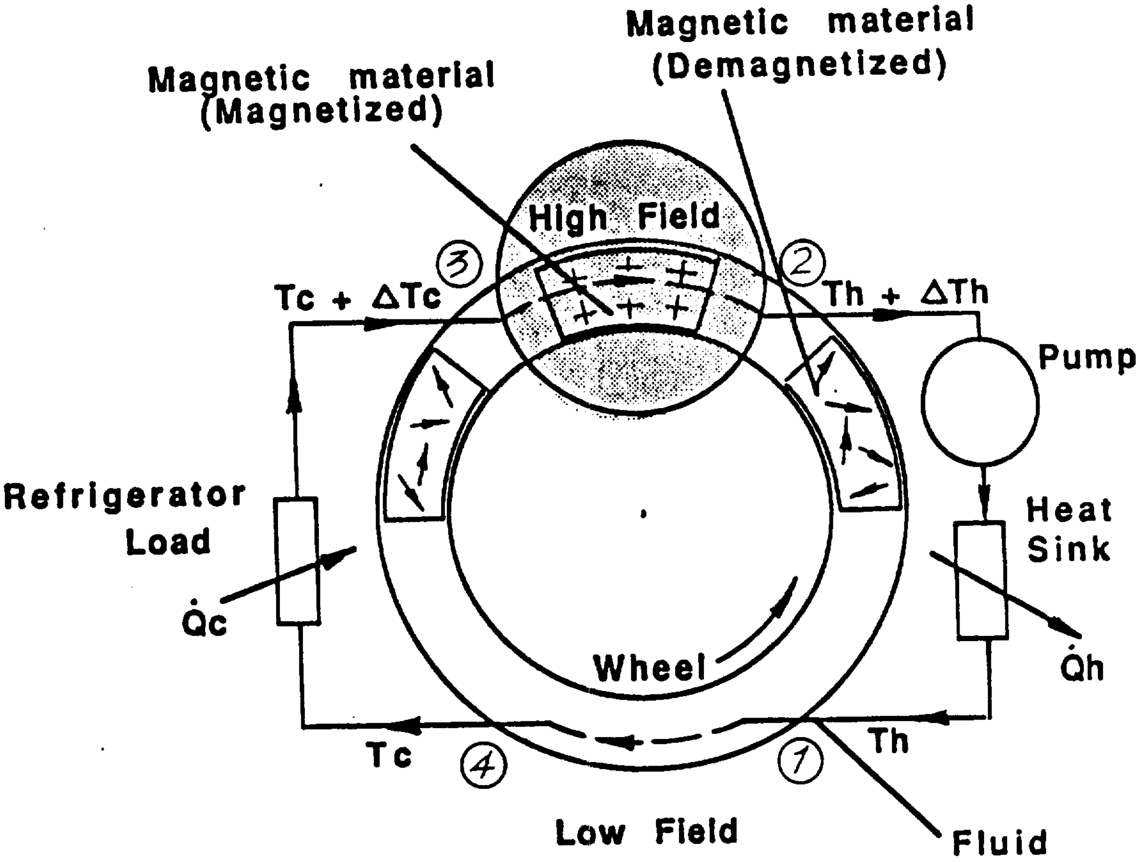


Figure 4.1. Magnetic Wheel Design

supercritical helium) is circulated opposite to the direction of rotation of the wheel. Circulated fluid is cooled by the demagnetizing material on the bottom side and is warmed by the magnetizing material on the top side. The operations are as follows:

(a) The magnetic material is adiabatically magnetized as it rotates into the high magnetic field region, heating from Th to Th + Th.
(b) As it rotates through the high magnetic field region the counter flowing fluid cools the magnetic material to temperature Tc + Tc.
(c) The material is separated from the fluid just before adiabatic demagnetization cools the magnetic material to Tc before the counter flowing fluid warms the rotating magnetic material back to Th to complete the cycle.

The fluid at the hot side of the wheel is cold in the heat exchanger (Heat sink) from Th + Th to Th; the corresponding fluid in the cold heat exchanger (Refrigerator load) is heated from Tc to Tc + Tc.

In order to make the refrigerator efficient, a high efficiency pump is required to circulate the fluid (such as helium gas) through the cycle. In the actual device, the pump should be placed at the location with highest possible temperature.

4.2 THE DESIGN OF MAGNETIC REFRIGERATOR. The design of the magnetic refrigerator configurations are basically done by iterations of a computer simulation model.

4.2.1 The Computer Simulation Model. The computer model was developed by EG & G Idaho National Engineering Laboratory. It is a model with capacities to run different types of refrigerator with different magnetic materials.

4.2.1.1 Program Features of the Computer Simulation Model.

Structured programming
Forty separate subroutines for the follow functions:
- Refrigerant entropy calculation and table building
- Refrigerant entropy from table
- Recuperator fluid data
- Heat transfer correlations

- Pressure drop correlations
- Adiabatic temperature rise
- Data input and output
- Plotting
- Iteration control

4.2.1.2 Use of the Computer Simulation Model. This model is an interactive computer program to simulate the performance of a rotor recuperative magnetic refrigerator. The computer prompts for data to define the refrigerator configuration. After all data values are entered (data values and their significance and data entry sheet are shown in Table 4.1, and Fig. 4.2), the program prompts for the name of file containing entropy data. This file contains entropy data for various working materials (see Table 4.2) and MAPS of magnetic field profiles to allow simulation of refrigerator with any circumferential field variation. The program also prompts for the name of a file containing recuperator fluid data. The current file contains data for several recuperator fluids (see Table 4.3). The program will print out a summary of refrigerator performance, and the computer will prompt for the name of a file to write a detailed report of refrigerator configuration and performance. The computer will then ask for increment rotation time. This is useful for comparing one refrigerator to another since each may have optimum performance at different speeds. If rotation time increment are given, a plot file will be created and an efficiency versus power density will be plotted (see Fig. 4.3). After runs for speeds entered are completed other variables can be changed until desirable configurations of the magnetic refrigerator found by computer iterations.

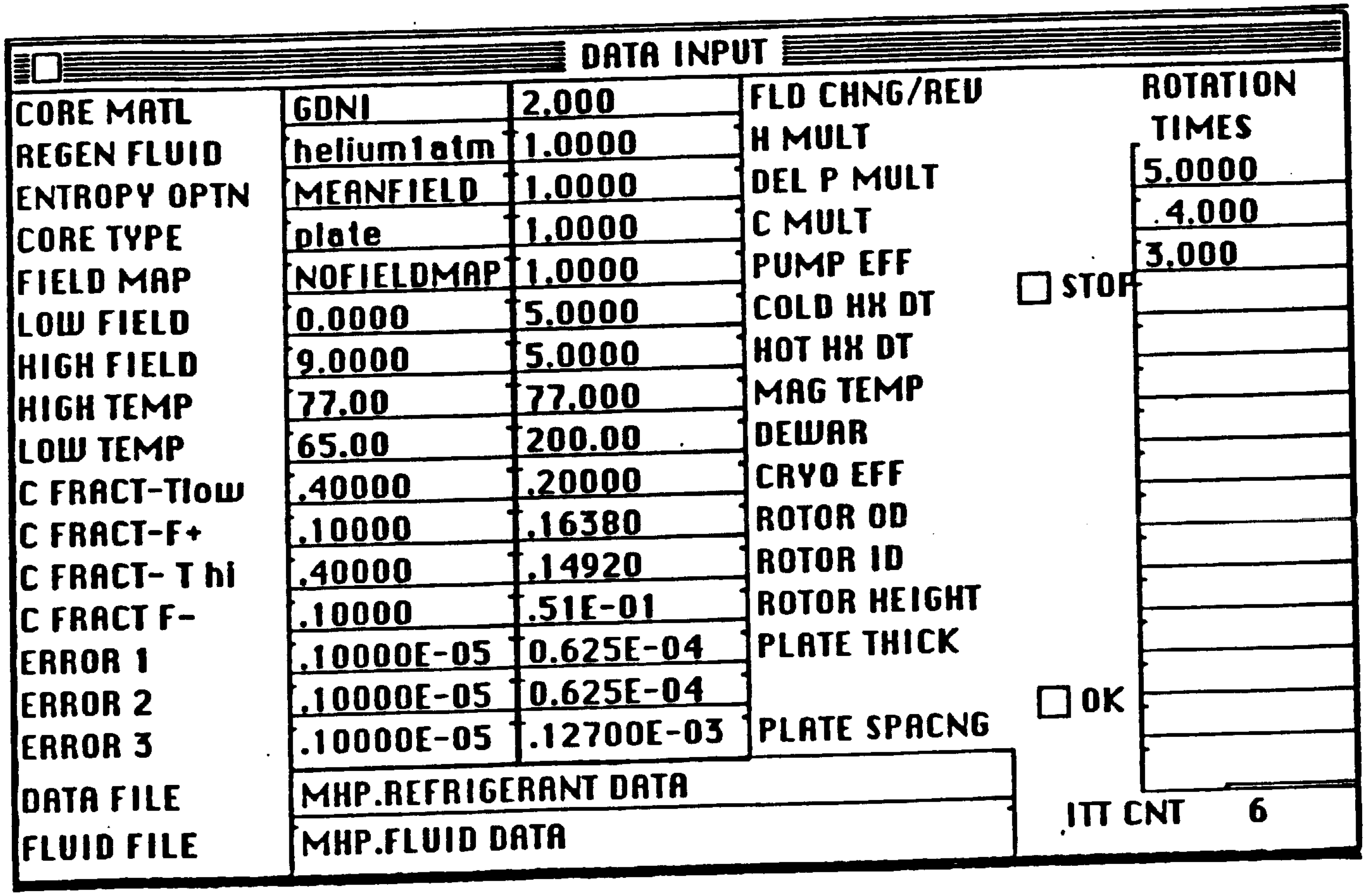
4.2.1.3 Computer Model Iteration Method. See Chart 4.1.

4.2.1.4 Computer Output and Design of Magnetic Refrigerator. An example illustrates the procedures of determining the size of refrigerator by using the computer model.

Example: To find the desirable size of the magnetic material plate by selected data input.

No.	Term	Definition	Units
1	CORE MATL	Core material	
2	REGEN FLUID	Regenerator fluid (or recuperator fluid)	
3	ENTROPY OPTN	Entropy calculation option	
4	CORE TYPE	Core type (plate/screen/packed bed)	
5	FIELD MAP	Field map name	
6	LOW FIELD	Low field strength	Teslas
7	HIGH FIELD	High field strength	Teslas
8	HIGH TEMP	Heat pump internal TH (delivery temp.)	k
9	LOW TEMP	Heat pump internal TL (input temp.)	k
10	C FRACT-Tlow	Circumference fraction for recuperative heating	decimal fraction
11	C FRACT-F+	Circumference fraction for field rise	decimal fraction
12	C FRACT-Thi	Circumference fraction for recuperative cooling	decimal fraction
13	C FRACT-F-	Circumference fraction for field drop	decimal fraction
14	ERROR 1		
15	ERROR 2		
16	ERROR 3		
17	FLD CHNG/REV	Field change/rev. (cycles /rev.)	
18	H MULT	Heat transfer coefficient multiplier	
19	DEL P MULT	Presssure drop multiplier	
20	C MULT	Thermal conduction multiplier	
21	PUMP EFF	Pump efficiency	decimal fraction
22	COLD HX DT	Temperature drop in cold heat exchanger	k
23	HOT HX DT	Temperature drop in hot heat exchanger	k
24	MAG TEMP	Magnet operating temperature	k
25	DEWAR	R-value of magnet dewar	W/K-m**2
26	CRYO EFF	Efficiency (relative to Carnot COP) of magnet cooler	decimal fraction
27	ROTOR OD	Rotor OD	m
28	ROTOR ID	Rotor ID	m
29	ROTOR HEIGHT	Rotor stack height	m
30	PLATE THICK	Plate thickness	m
31	PLATE SPACNG	Space between plates	m
32	ROTATION TIMES		S/Rev.

Table 4.1. Data Values and Definitions



DATA INPUT

CORE MATL	GDNI	2.000	FLD CHNG/REV	ROTATION TIMES
REGEN FLUID	helium1atm	1.0000	H MULT	5.0000
ENTROPY OPTN	MEANFIELD	1.0000	DEL P MULT	4.000
CORE TYPE	plate	1.0000	C MULT	3.000
FIELD MAP	NOFIELDMAP	1.0000	PUMP EFF	
LOW FIELD	0.0000	5.0000	COLD HX DT	
HIGH FIELD	9.0000	5.0000	HOT HX DT	
HIGH TEMP	77.00	77.000	MAG TEMP	
LOW TEMP	65.00	200.00	DEWAR	
C FRACT-Tlow	.40000	.20000	CRYO EFF	
C FRACT-F+	.10000	.16380	ROTOR OD	
C FRACT- T hi	.40000	.14920	ROTOR ID	
C FRACT F-	.10000	.51E-01	ROTOR HEIGHT	
ERROR 1	.10000E-05	0.625E-04	PLATE THICK	
ERROR 2	.10000E-05	0.625E-04		
ERROR 3	.10000E-05	.12700E-03	PLATE SPACNG	
DATA FILE	MHP.REFRIGERANT DATA			
FLUID FILE	MHP.FLUID DATA			

Figure 4.2. Data Input Sheet

GDNI	Gadolinium nickel
GDNI40	Gadolinium nickel with artificial Curie point of 40 K
GDNIMIX	Gadolinium nickel with difference Curie points (17 and 77 K) mixed
GDTC293	Gadolinium with T_C of 293 K
GDTC304	Gadolinium with T_C of 304 K
GDTC320	Gadolinium with T_C of 320 K
GDTC340	Gadolinium with T_C of 340 K
GDTC360	Gadolinium with T_C of 360 K
GDTC380	Gadolinium with T_C of 380 K
GDTC400	
GDTC420	
GDTC440	
GDTC460	
GDTC480	
IRON	Only includes mean field model, which is inaccurate for iron
COBALT	Only mean field model, not accurate
Y2CO400525	Mix of $Y_2(Co_xFe_{1-x})_{17}$ with 400 and 525 K T_C
Y2CO416.2	$Y_2(Co_xFe_{1-x})_{17}$ with T_C of 416.2 K
Y2CO419	$Y_2(Co_xFe_{1-x})_{17}$ with T_C of 419 K
Y2COFE400	$Y_2(Co_xFe_{1-x})_{17}$ with 400 K T_C
Y2COFE380	$Y_2(Co_xFe_{1-x})_{17}$ with 380 K T_C
Y2COFE525	$Y_2(Co_xFe_{1-x})_{17}$ with 525 K T_C
SMCOFE400	$Sm_2(Co_xFe_{1-x})_{17}$ with 400 K T_C
GADOLINIUM	Gadolinium
STRGT9.480	Fictitious material with straight T-S line; 400 K T_C. Data provided at 0 & 9 T.
CONCP9.480	Fictitious material with constant specific heat as a function of temperature.

Table 4.2. Working Material Names in Computer Files

WATER	Liquid 200 to 588 K
METHANOL	Liquid 200 to 513 K
CO2-1ATM	Gas at 1 atmosphere, 220 to 600 K
HELIUM1ATM	Gas at 1 atmosphere, 4.21 to 8110K
AIR-1ATM	Gas at 1 atmosphere, 255 to 755 K
SODIUM	Liquid metal, 339 to 977 K
FF-DXE	Ferromagnetic fluid with 400 K T_C, saturation magnetization of 150 to 200 gauss, and 1-1-Di (ortho zylyl) Ethane (DXE) carrier fluid; 350 to 473 K
FF-ISOPARH	Ferromagnetic fluid as above, except with Isoparaffinic hydrocarbon carrier fluid
DOWTHERM A	Dowtherm A heat transfer fluid, 323 to 673 K
FREON R113	Liquid 256 to 477 K
MERCURY	Liquid metal 274 to 523 K
H2-1ATM	Gas at 1 atmosphere, 20 to 80 K

Table 4.3. Recuperator Fluids

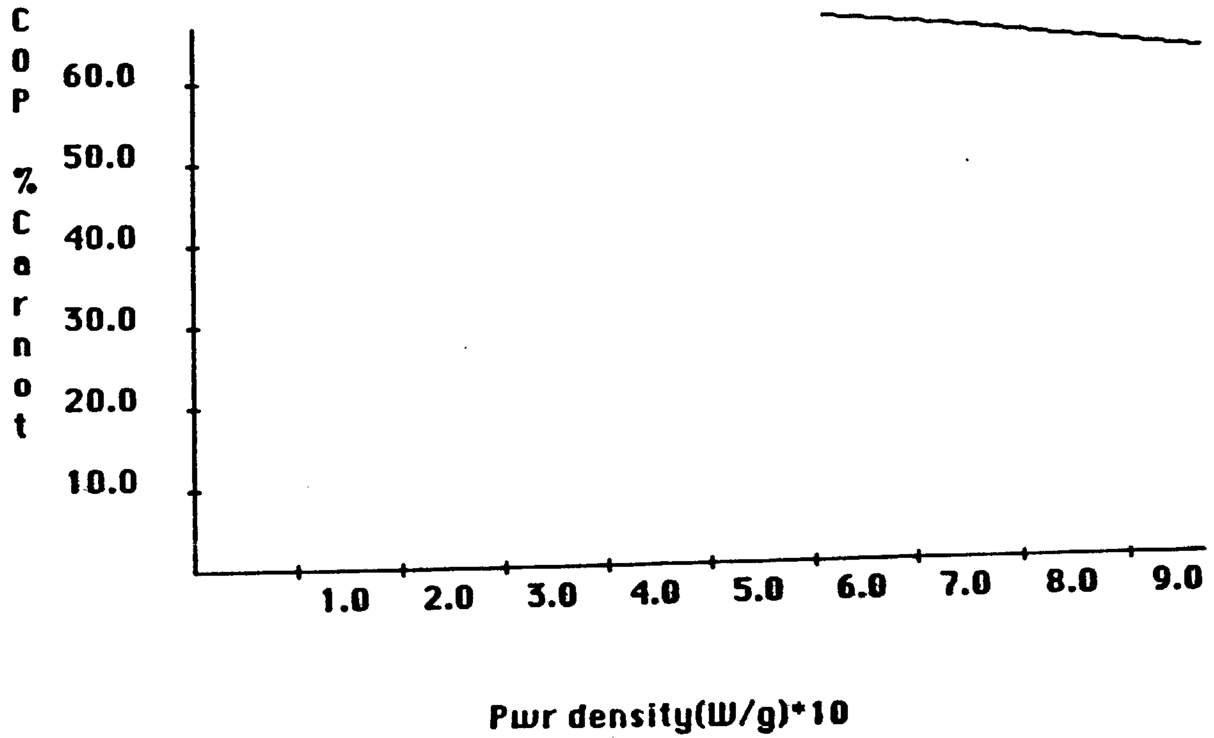


Figure 4.3. COP vs Power Density

CHART 4.1 CALCULATIONAL METHOD

```
GUESS HEAT CAPACITY RATIO (HCR) - FLUID TO REFRIGERANT
    INITIAL TEMPERATURE STACKUP
        ENERGY BALANCE
        HEAT TRANSFER RATES
        MODIFY TEMPERATURES AS REQUIRED
    DETERMINE EFFICIENCY AND POWER DENSITY
    FIBINACCI SEARCH;  NEW HCR TO APPROACH MAXIMUM
    EFFICIENCY.
PRINT RESULTS
RUN NEXT SPEED
```

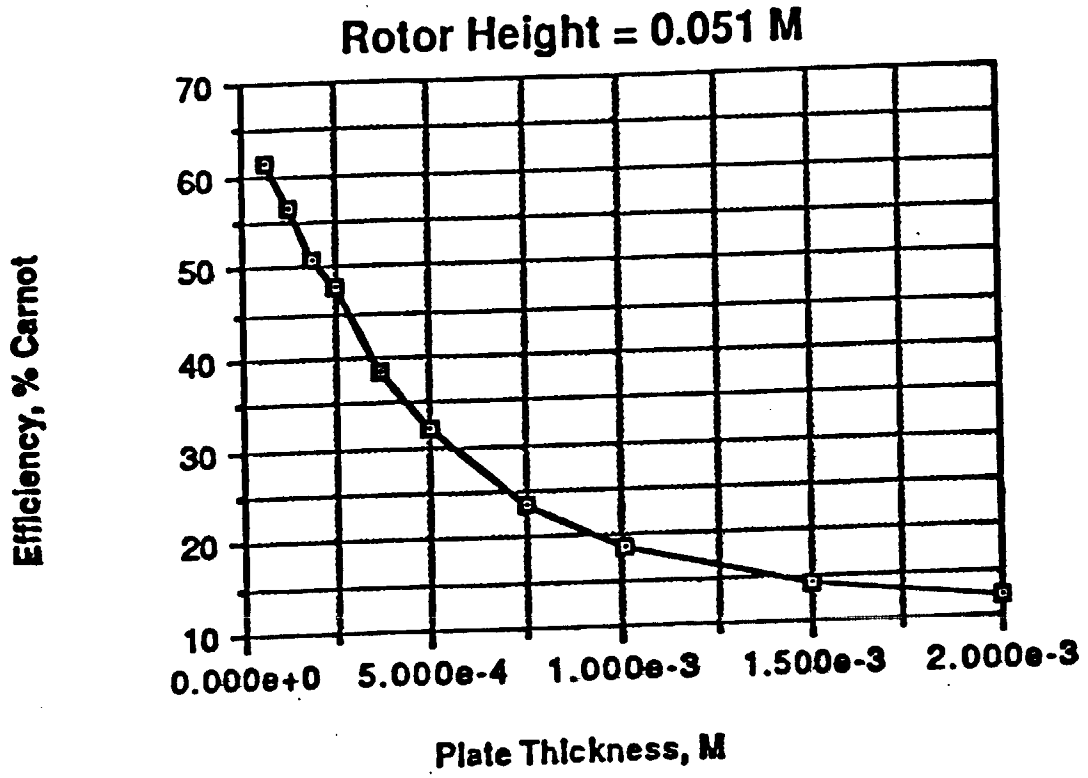


Figure 4.4. Efficiency vs Rotor Plate Thickness

Procedures:

(a) Input selected data into the data sheet.
Major data selected for this example are listed below;

Core material - Gadolinium Nickel
Recuperator fluid - Helium at 1 atm.
Core type - Plate
High temperature - 77K
Low temperature - 65K
Rotor height - 0.051 m
Rotor inside diameter - 0.1492 m
Rotor outside diameter - 0.1638 m
Plate thickness - 0.625E-4 m

(b) Run computer with different rotor plate thicknesses.
(c) Plot efficiency (% of Carnot cycle) versus plate thickness and search for a thickness with highest refrigerator efficiency. (see Fig. 4.4)
(d) Compare the recuperator flow rate at this thickness with the flow rate of helium pump at highest pump efficiency.
(e) If the recuperator flow rate of the magnetic refrigerator and the helium pump flow rate are comparable, then, the plate thickness is proper for the helium pump.

Computer Output:

Major outputs are:

COP with cryocooler - 3.95, Efficient (% Carnot) - 61.55
COP w/o cryocooler - 4.19, Efficient (% Carnot) - 65.24
Recuperator flow rare - 0.0147628 kg/s

Design dicisions: The plate thickness versus efficiency curve indicates that at plate theckness equals to 0.000625 m the refrigerator has the highest efficiency and the flow rate is 0.0147628 kg/s. If this flow rate is within the range of helium pump flow rate at highest efficiency then, the plate thickness is proper size for the helium pump.

Complete computer print out (including Entropy table, input data, and output results etc.) are shown in the Appendix section.

5 CONCLUSION

The supercritical helium pump performance information and test results and a revised pump testing procedure will be provided by the Boeing Aerospace Operation Contractor in the future.

The computer model of magnetic refrigerator is a powerful system which has been demonstrated to sucessfully function in a design and analysis role. Findings from which would suggest the following conclusions:

(a) The magnetic refrigerator only operate with a low temperature difference. Because of this fact that heat transfer should be an important design concern.

(b) The magnetic refrigerator can not operate with packed bed particles, simply because poor recuperative heat transfer. Research to develop improved recuperative heat transfer techniques is needed.

(c) Intimate thermal contact between the magnetic material and the heat transfer liquid is necessary.

(d) It is desirable to make the exposed area of the magnetic material as large as possible.

REFERENCES

1. P. L. Wang, "Experimental Apparatus and Procedures for Testing and Evaluating a Supercritical Helium Pump," NASA/ ASEE Summer Faculty Fellowship Program for Kennedy Space Center, 1987 Research Report, December, 1987

2. Harry J. Sauer and Ronald H. Howell, "Heat Pump Systems," John Wiley & Sons, New York 1983

3. Rondall F. Barron "Cryogenic Systems," 2nd Edition, Oxford University press, N. Y. 1985

APPENDIX

Complete Computer Output Sheet

```
ENTROPY TABLE: T, SL, SH, SINTL, SINTH, FL,FH
 45.00   98.7412   84.9555  .0000E+00  .0000E+00    .00   9.00
 46.31  104.4245   89.9346  .2595E+03  .2273E+03    .00   9.00
 47.61  110.1870   94.9692  .5301E+03  .4637E+03    .00   9.00
 48.92  115.9982  100.0271  .8106E+03  .7079E+03    .00   9.00
 50.23  121.8594  105.1074  .1101E+04  .9597E+03    .00   9.00
 51.53  127.7748  110.2123  .1402E+04  .1219E+04    .00   9.00
 52.84  133.7263  115.3217  .1713E+04  .1486E+04    .00   9.00
 54.15  139.7196  120.4387  .2033E+04  .1760E+04    .00   9.00
 55.45  145.7467  125.5528  .2364E+04  .2040E+04    .00   9.00
 56.76  151.8031  130.6569  .2703E+04  .2326E+04    .00   9.00
 58.07  157.8892  135.7486  .3053E+04  .2619E+04    .00   9.00
 59.37  163.9983  140.8181  .3412E+04  .2916E+04    .00   9.00
 60.68  170.1299  145.8617  .3780E+04  .3219E+04    .00   9.00
 61.98  176.2791  150.8709  .4157E+04  .3526E+04    .00   9.00
 63.29  182.4464  155.8431  .4543E+04  .3838E+04    .00   9.00
 64.60  188.6267  160.7693  .4938E+04  .4153E+04    .00   9.00
 65.90  194.8188  165.6445  .5342E+04  .4471E+04    .00   9.00
 67.21  201.0253  170.4673  .5755E+04  .4792E+04    .00   9.00
 68.52  204.6784  175.2217  .6003E+04  .5115E+04    .00   9.00
 69.82  207.5998  179.9125  .6205E+04  .5439E+04    .00   9.00
 71.13  210.5093  184.5317  .6410E+04  .5765E+04    .00   9.00
 72.44  213.4007  189.0695  .6618E+04  .6090E+04    .00   9.00
 73.74  216.2829  193.5312  .6828E+04  .6416E+04    .00   9.00
 75.05  219.1451  197.9028  .7041E+04  .6742E+04    .00   9.00
 76.36  221.9922  202.1867  .7257E+04  .7066E+04    .00   9.00
 77.66  224.8283  206.3850  .7475E+04  .7389E+04    .00   9.00
 78.97  227.6376  210.4809  .7695E+04  .7710E+04    .00   9.00
 80.28  230.4357  214.4895  .7918E+04  .8029E+04    .00   9.00
 81.58  233.2156  218.4040  .8143E+04  .8346E+04    .00   9.00
 82.89  235.9734  222.2214  .8370E+04  .8660E+04    .00   9.00
 84.20  238.7194  225.9540  .8599E+04  .8972E+04    .00   9.00
 85.50  241.4400  229.5903  .8830E+04  .9280E+04    .00   9.00
 86.81  244.1440  233.1421  .9063E+04  .9586E+04    .00   9.00
 88.12  246.8341  236.6152  .9298E+04  .9890E+04    .00   9.00
 89.42  249.4954  239.9984  .9534E+04  .1019E+05    .00   9.00
 90.73  252.1445  243.3120  .9773E+04  .1049E+05    .00   9.00
 92.04  254.7729  246.5513  .1001E+05  .1078E+05    .00   9.00
 93.34  257.3788  249.7185  .1025E+05  .1108E+05    .00   9.00
 94.65  259.9726  252.8275  .1050E+05  .1137E+05    .00   9.00
 95.95  262.5389  255.8668  .1074E+05  .1166E+05    .00   9.00
```

```
ROTARY MAGNETIC HEAT PUMP:  RUN #   1    8- 3-88      16:38: 8

DATA:                                      SOURCE TEMP (K)      65.00  MULTIPLIERS:
         CORE MATERIAL GDNI            DELIVERY TEMPERATURE     77.00  DELTA P 1.00
RECUPERATOR MATERIAL HELIUM1ATM            TEMP ASSYMETRY        .5833         H 1.00
      FIELD MAP NAME NOFIELDMAP            HIGH FIELD  (T)       9.00   COND K 1.00
  ENTROPY CALCULATION MEANFIELD            LOW  FIELD  (T)        .00
             CORE TYPE PLATE             ROTATION TIME  (S)      5.00     ITTERATION
          ROTOR OD  (M)   .16380         CYCLES/REVOLUTION         2       CLOSURE
              ROTOR ID    .14920           PUMP EFFICIENCY       1.00   ERR1   .1D-05
           CORE HEIGHT    .05100      angl FRACTIONS                    ERR2   .1D-05
  PLATE THICKNESS  (M)    .6250D-04             FIELD RISE   .10000     ERR3   .1D-05
          SPACING  (M)    .1270D-03     RECUPERATIVE HEAT    .40000
        APPERTURE  (M)    .6250D-04             FIELD DROP   .10000
 HEAT EXCHANGER                        RECUPERATIVE COOL      .40000
          HOT APPROACH 5.00000             MAGNET OP TEMP      77.00
         COLD APPROACH 5.00000             CRYOCOOLER EFF      .2000



 RESULTS
           COP WITH CRYOCOOLER   3.95                 EFFICIENCY  (% CARNOT)   61.55
           COP W/O  CRYOCOOLER   4.19                 EFFICIENCY  (% CARNOT)   65.24
     CONDUCTION IN FLUID  (W)  .513D-02          EFFICIENCY CRYO & EXT HX     10.97
     CONDUCTION IN CORE   (W)  .811D+00              POWER DENSITY  (W/KG)    603.43
        HEAT  INPUT RATE  (W)  .2414D+03         (W/M**2) MAGNET AREA  .4259D+06
        HEAT OUTPUT RATE  (W)  .3171D+03        (W/M**3) MAGNET VOLUME .3465D+07
        WORK INPUT TOTAL  (W)  .8030D+02 SOURCE FLUID TEMP CHANGE  (K)    1.539
           MAGNETIC WORK  (W)  .7576D+02 LOAD   FLUID TEMP CHANGE  (K)    2.021
               FLOW WORK  (W)  .6136D+01   FLUID/CORE HEAT CAP. RATIO    .9943
               DISK WORK  (W)  .1554D-08      CORE MASS RATE  (KG/SEC)  .1051D+00
         CRYOCOOLER WORK  (W)  .4540D+01     CRYOCOOLER HEAT GAIN  (W)  .3135D+00

   CONFIGURATIONAL INFORMATION:             RECUPERATOR FLUID:
                     CORE MASS  (KG)  .5255D+00         DENSITY  (KG/M**3)  .1036D+02
      TOTAL ROTOR VOLUME  (M**3)  .1830D-03             VISCOSITY  (PA-S)  .6603D-05
            METAL VOLUME  (M**3)  .6037D-04        CONDUCTIVITY  (W/M-K)  .4991D-01
           FREE VOLUME FRACTION    .670         SPECIFIC HEAT (J/KG-K)  .5661D+04
           FREE AREA    FRACTION    .670      REYNOLDS NUMBER (HT CORR)  .2198D+04
              TOTAL SURFACE AREA .1932D+01     HYDRAULIC DIAMETER  (M)  .2497D-03
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STATE POINTS:          1         3         4         5         7         8
 FLUID TEMP (K)      75.508    76.953    77.105    65.014    63.731    64.346
 CORE  TEMP (K)      75.229    77.119    77.119    66.478    63.583    63.583
 ENTROPY (J/KG-K)  219.5376  204.6458  204.6458  167.7690  183.8224  183.8224
 FLUID-CORE DT(K)   .278603   .166625   .013797  1.464065   .148176   .763194
 FLUID T @A,B,C,D    76.986    77.000    63.864    65.000

PROCESSES BETWEEN STATE POINTS, PER MAGNET COIL:
 REGION                         1-4            1-8            5-8            4-5
 PINCH POINT TEMPERATURE(K)                   75.2294                      77.1193
 PINCH DELTA TEMPERATURE(K)                .278603E+00                  .137969E-01
 HEAT TRANSFER RATE (WATT)   .120708E+03   .256497E+03   .107284E+03   .277801E+03
 CORE ENERGY CHANGE (J)      .301770E+02   .256497E+03   .268209E+02   .277801E+03
 FLUID ENERGY CHANGE (J)     .301822E+02   .256477E+03   .268158E+02   .277822E+03
 DISK WORK INTO SYSTEM (J)  -.517819E-02   .207128E-01  -.517819E-02   .207128E-01
 HEAT BAL: FLUID-CORE+DISK   .103564E-01   .107650E-12  -.103565E-01   .112590E-04
 angl (DEGREES)               18.000000     72.000000     18.000000     72.000000
 PRESSURE DROP (PA)          .844222E+03   .844222E+03   .844222E+03   .844222E+03
 FLUID FLOW RATE (KG/S)      .147628E-01   .405900E-02   .147628E-01   .405900E-02
 H-T COEFFICIENT (W/K-M**2)  .196277E+04   .162838E+04   .196277E+04   .162838E+04
 FLUID-CORE REL VEL.(M/S)    .561366E+01   .166883E+01   .561366E+01   .166883E+01
 REYNOLDS NUMBERS (DELTA P)        2198.          654.         2198.          654.
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