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SUBJECT: Design of Cryogenic Heat Exchangers for a Superconducting Magnet

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ABSTRACT

Computer programs were written to design and simulate the behavior of three heat exchangers for cooling supercritical helium to 4.3°K at 4 atm. Helium, at 1, 3, or 5 gm/sec, is cooled by passing it through 0.635-cm-diam copper tubing immersed in a liquid nitrogen bath, through a copper, concentric tube, counter-current heat exchanger, and then through 0.635-cm copper tubing immersed in a liquid helium bath. The helium then enters a superconducting test magnet and finally passes through the annulus of the countercurrent exchanger before venting to the atmosphere. Several acceptable designs are presented that meet design and space limitations.

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1. SUMMARY

Computer programs were written to simulate the design of three heat exchangers for cooling helium to $\sim 4.3^\circ\text{K}$ at 4 atm. Helium first passes through a 0.635-cm-diam (0.25 in.) copper tube immersed in a nitrogen bath to cool the helium to $\sim 80^\circ\text{K}$. The helium then passes through the inner, 0.635-cm, copper tube of a concentric tube countercurrent heat exchanger before entering a 0.635-cm copper tube immersed in a helium bath for final cooling. The helium at $\sim 4.3^\circ\text{K}$ then passes through a magnet test section where it can receive a variable energy input from 0 to 100 W before passing through the 1.27×0.635 -cm (0.5×0.25 in.) shell of the countercurrent exchanger.

To design these heat exchangers, each exchanger was divided into many small segments with a pre-established temperature difference through each segment. Starting at the magnet test section, energy balances were taken around each segment to determine the necessary heat transfer surface areas and helium bath boiloff rate.

Based on the results of the computer calculations, cooling of helium to $\sim 4.3^\circ\text{K}$ could be attained by several proposed systems; however, some of the proposed systems require large countercurrent heat exchanger lengths which would be difficult to fit into the space available. Designs which reduce the countercurrent heat exchanger length increase helium bath boiloff rate or increase the helium temperature leaving the magnet. Several acceptable designs are presented.

2. INTRODUCTION

The Fusion Energy Division at ORNL is investigating power generation with fusion reactors. Since the advent of research in nuclear fusion, studies have been conducted on cryogenically cooling large superconducting magnets to contain plasmas. An experimental magnet section is being designed for investigation of forced, non-superconducting transients. It has been proposed to cool this magnet with helium at $\sim 4.3^\circ\text{K}$. To cool bottled helium from room temperature, three heat exchangers have been proposed using a liquid nitrogen bath, test section vent helium in a countercurrent exchanger, and a liquid helium bath (Fig. 1). The objective of this project was to design these heat exchangers to supply the magnet with helium at $\sim 4.3^\circ\text{K}$ and 4 atm.

Two of the three heat exchangers are to be placed in a dewar 133-cm high and 19.7 cm in diameter. The helium bath exchanger is to be immersed in ~ 61 cm of helium at the bottom of the dewar; whereas, the countercurrent heat exchanger is to occupy the space above the liquid helium. Also immersed in the helium bath is the magnet test section which is 46 cm long and 15 cm in diameter. The helium boiloff rate from the bath due to energy input from the magnet and helium bath exchanger was stipulated to be less than

20 gm/sec. The nitrogen bath exchanger is located outside the dewar and has no space limitations.

The method of attack was to develop a computer program to calculate the lengths of the three exchangers and helium boiloff rate as functions of magnet energy input, helium flow rate, and temperature difference between helium in the inside tube and the shell of the countercurrent exchanger at the helium bath junction. The most desirable designs which met all design specifications were then selected. In all designs, the pressure drop through the magnet was set at 0.1 atm and the inlet pressure to the magnet was set at 4 atm. Helium flow rates of 1, 3, and 5 gm/sec were considered for countercurrent temperature differences of 4 and 6°K and magnet energy inputs of 0, 50, and 100 W.

3. CORRELATIONS

3.1 Heat Transfer Coefficients and Pressure Drop

Two correlations were used to model heat transfer in the exchangers. The first relationship describes heat transfer from the tube walls as a function of temperature difference in the different boiling regimes. The second correlation relates heat transfer to Reynolds number and Prandtl number for forced convection fluid flow within the exchangers. Correlations of the heat flux and temperature difference between the wall temperature and the bulk fluid temperature were obtained (Figs. 2 and 3). Heat transfer in the nucleate, transition, and film boiling regions can be described with (6):

$$Q = CA(T_{\text{out}} - T_{\ell})^n \quad (1)$$

The constants C and n, for the different regimes and liquids, are given in Figs. 2 and 3.

The Dittus-Boelter and the modified Dittus-Boelter correlations (23) were employed to obtain the heat transfer coefficient for turbulent fluid flow in the tubes. These expressions relate Reynolds and Prandtl numbers to the Nusselt number:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (2)$$

At low temperatures the properties of supercritical helium vary greatly. Therefore, at temperatures below 30°K, Giarratano, Arp, and Smith recommend the modified Dittus-Boelter equation to account for property variations near the wall (10):

Region	C	n	$(T_{out} - T_{He})$ Range (°K)
(1) Nucleate Boiling	6.74	2.39	0 - 0.45
(2) Transition	0.55	-0.64	0.45 - 5.2
(3) Film Boiling	0.024	1.19	5.2 - up

$P = 1 \text{ atm}$

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BOILING HEAT TRANSFER CORRELATIONS
FOR LIQUID HELIUM

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FIG
3

$$Nu = 0.0259 Re^{0.8} Pr^{0.4} (T_w/T_b)^{-0.716} \quad (3)$$

Because the fluid properties vary with pressure as well as temperature, variation of pressure due to shear in the exchangers for turbulent flow is given by (3):

$$\Delta P = \frac{2F\rho v^2 L}{D} \quad (4)$$

The friction factor, F , for turbulent flow in tubes is (3):

$$F = \frac{0.0791}{Re^{0.25}} \quad (5)$$

Equation (5) is slightly modified for coiled tubes (5):

$$F = 0.08 Re^{-0.25} + 0.01 \left(\frac{D}{D_c}\right)^{0.5} \quad (6)$$

where D_c is the diameter of the coil. The resulting helium pressure change due to change in kinetic energy is given by the Bernoulli equation (ignoring elevation effects) as

$$\Delta P = \rho v(v_1 - v_0) \quad (7)$$

where v_1 and v_0 are the helium velocities leaving and entering a segment of tube, respectively. The sum of Eqs. (4) and (7) give the total pressure drop within the tube segment.

For the shell side of the countercurrent heat exchanger, four times the hydraulic radius, $4R_h$, replaced D in the Reynolds number and in Eqs. (4) and (6). For the annulus,

$$R_h = \frac{D_{io} - D_{out}}{4} \quad (8)$$

3.2 Physical Properties of Helium

Several physical properties of helium were tabulated as functions of temperature and pressure: viscosity (μ), density (ρ), thermal conductivity (k), specific heat (C_p), Prandtl number (Pr), and enthalpy (H). The temperature range was 4 to 300°K, and the pressure range was 1 to 8 atm. The data were taken from NBS Circular 631 (18). At a given pressure a series of linear approximations were made to represent each property variation with temperature. Linear interpolation is used to obtain the value of a physical property at a pressure other than those for which the property is plotted against temperature. The slopes and intercepts for the lines representing the physical properties at given pressures and within given temperature ranges are tabulated in the computer program subroutine presented in Appendix 10.1.4.

At temperatures between 30 and 300°K, all physical properties considered above except the density of helium are not significantly dependent on pressure; whereas in the temperature range of 4 to 30°K all physical properties of helium vary significantly with temperature and pressure.

4. HEAT EXCHANGER MATERIALS AND CONFIGURATION

The nitrogen bath and helium bath heat exchanger copper tubing has an inside diameter of 0.5 cm and an outside diameter of 0.635 cm. The tube in the nitrogen bath was straight; whereas, the tube used in the helium bath was wound in a coil, 15 cm in diameter. The countercurrent heat exchanger, also wound in a 15-cm coil, consisted of two concentric copper tubes. The inner tube had an inside diameter of 0.5 cm and an outside diameter of 0.635 cm. The outside tube had an inside diameter of 1.1 cm and an outside diameter of 1.27 cm.

5. COMPUTER PROGRAMS

5.1 Calculation Procedure

Each heat exchanger was divided into a large number of small exchanger elements with a set temperature difference established for each element. Energy balances were made around each element and were initiated at the inlet to the magnet test section. Calculation then proceeded backwards through the helium bath, countercurrent, and nitrogen bath heat exchangers. For the first incremental calculation, inlet and outlet pressures were taken to be equal. Once the pressure drop was calculated, the calculations were repeated with the new calculated pressures.

In calculating the incremental energy balances, it was first necessary to determine the energy loss, Q , in an element of fluid moving at a mass

flow rate, $\dot{M}$, with inlet and outlet specific enthalpies, H_0 and H_1 , respectively.

$$Q = \dot{M}(H_1 - H_0) \quad (9)$$

For temperatures greater than 30°K, this equation can be simplified to

$$Q = \dot{M} C_p (T_1 - T_0) \quad (10)$$

where T_0 and T_1 are inlet and outlet temperatures of the increment.

To determine the inside and outside tube wall temperatures in a calculation increment for the nitrogen and helium bath exchangers, three equations for the three modes of heat transfer are employed (forced convection, conduction, and boiling). The equation which describes convective heat transfer from the helium to the tube wall is

$$Q = hA_{in}(T_b - T_{in}) \quad (11)$$

To calculate the heat transfer coefficient, the Dittus-Boelter or modified Dittus-Boelter equation was used depending on the temperature of the helium. The Prandtl number was obtained from the helium physical property data and the Reynolds number was obtained from the helium mass flow rate, viscosity, and tube inside diameter or hydraulic radius in the case of the shell of the countercurrent exchanger. To use the modified Dittus-Boelter equation, values for the bulk and wall temperatures were also needed. These temperatures were guessed to determine the heat transfer coefficient and to perform the initial calculations. Then the calculations were repeated with the temperatures calculated from the prior run. At steady state, the same heat must be conducted through the tube wall.

$$Q = -k A_w \frac{dT}{dr} \quad (12)$$

Substituting $2\pi rL$ for A_w in Eq. (12) will result in the following equation after integration:

$$Q = \frac{2\pi Lk(T_{in} - T_{out})}{\ln(r_{out}/r_{in})} \quad (13)$$

Also, at steady state, the heat transferred from the outer wall of the tube to the boiling liquid must be equal to the forced convection and conduction heat transfer. For this calculation, Eq. (1) is used with the constants given in Figs. 2 and 3. Simultaneous solution of the three heat transfer equations then gives the desired wall temperatures. The heat transfer area may then be computed from Eq. (11).

For the countercurrent exchanger, the calculation increment was based on a set temperature rise in the bulk fluid in the shell. Since the fluid enthalpy entering and leaving the calculation increment can be found from the physical property data, the rate of heat transfer within the increment from the inside tube to the shell can be computed from Eq. (9). From an energy balance, the enthalpy increase of the helium in the shell must be matched with a corresponding enthalpy decrease of that in the inside tube. The temperature of helium entering the calculation increment in the inside tube can then be determined from the physical property data.

The heat transfer surface area was computed with Eq. (14).

$$A_{in} = \frac{Q}{U(T_t - T_s)} \quad (14)$$

Subscripts t and s represent the bulk fluid temperatures in the inner tube and shell, respectively. To use Eq. (14), the overall heat transfer coefficient, U, must be determined. If Eq. (11) is applied to both the shell and inner tube sides of the heat exchanger, and the temperature differences are isolated for the resulting two equations and Eq. (13), the three equations can be summed to give

$$T_t - T_s = \frac{Q}{hA_{in}} + \frac{Q}{hA_{out}} + \frac{Q \ln(r_{out}/r_{in})}{2\pi Lk} \quad (15)$$

Equation (15) is combined with Eq. (14) to give the overall heat transfer coefficient.

$$U = \frac{1}{D_{in} \left[\frac{1}{h_t D_{in}} + \frac{1}{h_s D_{out}} + \frac{\ln(D_{out}/D_{in})}{2k} \right]} \quad (16)$$

The pressure drop may now be determined from Eqs. (4) to (7) using the physical property data to determine the density and to calculate the velocity as $4\dot{M}/\pi D_{in}^2 \rho$ for the tubes and $4\dot{M}/\pi(D_{ic}^2 - D_{in}^2)\rho$ for the counter-

current exchanger annulus. The length, L , is determined by dividing the inside heat transfer area by the inside circumference of the tube. Once a new pressure is found for the high temperature side of the calculation increment, this pressure is used and the incremental calculations are repeated for the same increment until there is no further change in any of the calculated values.

5.2 Assumptions and Limitations of Programs

The computer programs have several limitations which should be noted. The helium bath heat exchanger program can only handle inlet temperatures of less than 30°K since enthalpy data in the subroutine for this program are for a temperature range of 4 to 30°K. Only for low helium flow rates or high magnet energy inputs will this limitation be important. The second limitation involves the use of a pressure of 8 atm for determining all physical property data at pressures above 8 atm. This characteristic of the subroutine for temperatures in the ideal gas range (above 30°K) will only seriously affect the density; consequently, for temperatures in the ideal gas range the ideal gas law was used for density determination. It should be noted that in none of the cases considered was the pressure above 8 atm while the temperature was below 50°K. The last limitation involves the use of four assumptions each of which are justified below.

The first assumption was the neglect of a static pressure head due to elevation changes. Without the static pressure, the lowest pressure drop along the helium bath and countercurrent exchangers occurred at a flow rate of one gm/sec. When the energy input from the magnet is 100 W, the inlet temperature to the magnet is 4.3°K, and the temperature difference between the hot and cold sides of the countercurrent heat exchanger at the inlet to the helium bath exchanger is 6°K, this pressure drop is 0.18 atm. Since the maximum elevation change in the dewar is about 135 cm and the maximum density of the helium is at the inlet to the magnet (0.134 gm/cm³), the maximum pressure drop along the exchangers from elevation changes is 0.017 atm. Although this is nearly 10% of the pressure drop due to shear and kinetic energy changes, the use of maximum helium density in the calculation is very conservative giving unreasonably high pressure drops. It is not expected to significantly affect any of the energy balances used in the computer programs; therefore, this component of pressure drop has been omitted.

The second assumption was the neglect of kinetic energy in the energy balances. The maximum velocity encountered is at the nitrogen bath exchanger inlet where it is 13,357 cm/sec. Per gram of helium, the energy loss by reducing this velocity to zero is 8.92 joules or less than 1% of the total energy lost in the nitrogen exchanger. In both the countercurrent and helium bath exchangers, the maximum kinetic energy change was also less than 1%.

The third assumption is the neglect of axial conduction in the helium and along the tube wall. The maximum conductivity in the axial direction

is in copper which is, at 300°K, 2.4 W/cm-°K. The shortest nitrogen bath heat exchanger length encountered in this analysis is 182 cm over which a temperature drop of 218°K occurs. The area available for axial conduction is 0.120 cm²; therefore, the axial conduction is of the order of 0.3 W. For helium, the conductivity at room temperature and 8 atm is 2.62×10^{-3} W/cm-°K. The area available for axial conduction is 0.196 cm² so that the axial conduction in helium is of the order of 6×10^{-4} W. Since the total heat transferred radially for the nitrogen bath heat exchanger considered here was 1141 W, axial conduction can safely be neglected.

The last assumption is the neglect of the transition boiling regime in the nitrogen and helium bath heat exchangers. These regimes were replaced with the film boiling regime. This change is conservative in that the resulting heat exchanger will have greater heat transfer surface than in the case where the transition boiling regime was used. It should be noted, however, that this change will introduce a discontinuity of temperature in the wall of the heat exchanger which cannot exist, so some type of transition boiling regime must exist. The discontinuity introduces the problem of deciding in which direction to take incremental energy balances. Starting from the end of the heat exchanger where film boiling is occurring, the film boiling regime will prevail over a larger portion of the heat exchanger than if energy balance increments were initiated at the other end, as in the cases described in this report. The conservative elimination of the transition boiling regime may therefore be more than offset by this method of calculation.

6. RESULTS

The results of the heat exchanger design are tabulated in Table 1 and plotted in Figs. 4 through 7. Figures 4 and 5 present data on helium bath boiloff rate and Figs. 6 and 7 present data on heat exchanger length.

Boiloffs greater than 20 gm/sec are considered unacceptable. Figures 4 and 5 clearly indicate that in no case considered does this occur. To reduce boiloff to a minimum and still allow a magnet energy input of 100 W, either the countercurrent heat exchanger temperature drop at the helium bath junction or helium flow rate must be held to a minimum. Although a lower countercurrent exchanger temperature drop gives a smaller helium boiloff rate, it also increases the length of the countercurrent exchanger (see Figs. 6 and 7). The countercurrent exchanger coil is 15 cm in diameter and therefore requires two windings per meter of length. To give some separation between each winding, a minimum of 3.2 cm of dewar height are required per meter of heat exchanger length. Since it is desired to use no more than 50.8 cm (20 in.) of dewar height for the countercurrent exchanger, its length should be kept under 16 meters. This is accomplished in all cases with a countercurrent temperature drop of 6°K which results in high helium boiloff rates. However, at a temperature difference of 4°K, only a flow rate of one gm/sec is acceptable for magnet energy inputs of 100 W resulting in high magnet exit temperatures.

Table 1. Tabulation of Results

Magnet Inlet Temperature = 4.3°K Magnet Inlet Pressure = 4.0 atm								
Q_M (W)	Flow Rate (gm/sec)	ΔT^1 (°K)	T_{bc} (°K)	P_b^2 (atm)	L_{He} (m)	L_{CC} (m)	L_{N_2} (m)	Boiloff (gm/sec)
0	3	4	4.31	7.34	4.74	16.88	6.65	4.97
0	3	6	4.31	7.02	5.05	11.94	6.60	6.95
50	3	4	6.03	7.48	5.01	17.81	6.78	6.68
50	3	6	6.03	7.11	5.33	12.46	6.59	8.48
100	1	4	19.09	4.32	4.19	15.06	1.83	5.81
100	1	6	19.09	4.23	4.30	9.79	1.82	6.32
100	3	4	8.17	7.64	5.37	18.96	6.90	8.57
100	3	6	8.17	7.20	6.11	12.77	6.65	10.37
100	5	4	6.42	13.83	6.89	19.68	15.31	11.67
100	5	6	6.42	13.21	8.36	13.52	14.68	14.65

¹At helium bath junction for countercurrent exchanger.

²To nitrogen bath exchanger.

Helium heat exchanger lengths (Figs. 6 and 7) are all within acceptable limits. If a coil diameter of 1.7 cm is used, the annulus between the magnet and the dewar wall gives additional heat exchanger space. High flow rates give greater heat transfer surface areas since the heat transfer rate is directly proportional to the flow rate, whereas heat flux is only proportional to the flow rate to the 0.8 power. The higher helium bath inlet temperature for low flow rates does not appear to be great enough to overcome this effect. Even under the worst conditions considered, a flow rate of 5 gm/sec, an energy input of 100 W, and a temperature drop in the countercurrent heat exchanger at the helium bath junction of 6°K, the helium heat exchanger length is only 8.36 meters which is well within the space available.

The nitrogen bath heat exchanger length appears to be strongly dependent only on flow rate (Fig. 7). From the arguments given in the preceding paragraph, it would seem that the nitrogen bath heat exchanger length should be less than proportional to flow rate; however, Fig. 7 indicates that the reverse is true. In this case a smaller tube heat transfer coefficient from a smaller flow rate actually increases the heat transfer rate. Greater resistance to heat transfer in the heat exchanger results in a smaller temperature drop between the outside heat transfer surface and the boiling nitrogen, thus resulting in nucleate rather than film boiling over a much larger surface area of the exchanger. The best design for the nitrogen heat exchanger thus appears to be a bundle of tubes in parallel so that lower flow rates can be achieved through each tube.

Although the modified Dittus-Boelter equation was used in the countercurrent exchanger designs for temperatures below 30°K, it was not incorporated into the helium bath exchanger design where the Dittus-Boelter equation was used. It was first thought that the Dittus-Boelter equation would be more conservative giving longer heat exchangers than the Modified Dittus-Boelter equation since higher heat transfer coefficients are obtained with the latter. The higher heat transfer coefficient, however, increases the heat transfer tube length over which film boiling occurs. This effect is dominant so that use of the Modified Dittus-Boelter equation will increase heat exchanger length. This would not occur, however, if one were to use data on heat transfer in a transition boiling region (6) which is found to give higher heat transfer coefficients than the film heat transfer correlation. The conservative use of the film boiling correlation in the transition boiling region should more than offset any benefits gained by the use of the Dittus-Boelter equation.

7. CONCLUSIONS

Heat exchangers can be constructed which will meet all design specifications. Two tradeoffs are noted. First, increased temperature drop in the countercurrent exchanger at the helium bath junction reduces countercurrent exchanger length but increases helium boiloff. Secondly, increased flow rate reduces magnet outlet temperature but increases helium boiloff.

8. RECOMMENDATIONS

To make the design programs more precise, the following changes are recommended:

1. Use the modified Dittus-Boelter equation in the helium bath.
2. Determine more accurate heat transfer correlations for the transition boiling regime.
3. Repeat calculations starting at the nitrogen bath inlet so that film boiling precedes nucleate boiling and compare with the present results.
4. Take the temperature integral of helium heat capacity from an established base state to determine the enthalpy rather than interpolate from tabulated enthalpy data. This function would utilize tabulated heat capacity data so the resulting correlation of enthalpy versus temperature would not be linear. This relationship would make the enthalpy change calculations more consistent when going from the ideal to the non-ideal gas conditions.
5. Consolidate the three computer programs into one to make the programs more convenient to use.

9. ACKNOWLEDGMENTS

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10. APPENDIX

10.1 Computer Programs

Program listings and flow charts for the three heat exchangers follow.

10.1.1 Helium Bath Exchanger

```

00100 C      THIS PROGRAM IS USED TO DESIGN THE LIQUID HELIUM
00200 C      BATH HEAT EXCHANGER. THE GENERAL METHOD OF CALCULATION
00300 C      IS BY SPECIFYING THE CONDITIONS DESIRED GOING
00400 C      INTO THE MAGNET TEST SECTION. THE PROGRAM BACKSTEPS
00500 C      UNTIL THE TEMPERATURE AT THE INLET TO THE EXCHANGER
00600 C      IS WITHIN SOME TEMPERATURE OF THE MAGNET EXIT STREAM
00700 C      THE AREA, LENGTH, AND PRESSURE DROP ENCOUNTERED IN THE
00800 C      EXCHANGER ARE THEN OUTPUTED. PROFILES OF THE TEMPERATURES
00900 C      ARE GIVEN.
01000 C      TINLT IS THE TEMP RANGE THAT SPECIFIES HOW CLOSE
01100 C      THE INLET TEMP. SHOULD BE TO THE MAGNET OUTLET TEMP
01200 C      TINLT=4.0
01300 C      P IS THE PRESSURE AT THE MAGNET TEST SECTION INLET
01400 C      P=4.0
01500 C      QM IS THE HEAT LOST BY THE MAGNET (WATT)
01600 C      QM=100.0
01700 C      TMI IS THE TEMPERATURE AT THE MAGNET TEST SECTION INLET
01800 C      TMI=4.3
01850 C      TWALL IS THE OUTSIDE WALL TEMPERATURE IN THE CALCULATION INCREMENT
01900 C      TWALL=TMI
02000 C      TINT IS THE INCREMENT OF TEMPERATURE FOR EACH SECTION
02100 C      TINT=.1
02200 C      AM IS THE FLOW RATE OF THE HELIUM (GRAMS/SEC)
02300 C      AM=1.0
02400 C      ADIAM IS THE INSIDE TUBE DIAMETER (CM)
02500 C      ADIAM=.5
02600 C      DIAM IS THE OUTSIDE TUBE DIAMETER (CM)
02700 C      DIAM=.635
02800 C      THE IS THE HELIUM BATH TEMPERATURE
02900 C      THE=4.2
03000 C      QMEX IS THE CALCULATED HEAT LOSS BY THE MAGNET TEST SECTION
03001 C      QTOT IS THE ACCUMULATIVE HEAT LOST THROUGH THAT PORTION OF
03002 C      HEAT EXCHANGER COVERED BY THE CALCULATION
03100 C      QTOT=0
03200 C
03300 C      THIS SECTION OF THE PROGRAM CALCULATES THE TEMPERATURE
03400 C      RISE OF THE HELIUM STREAM FOR THE HEAT INPUT BY THE MAGNET
03500 C      THEM2=THI+TINT
03600 C      THEM1=TMI
03700 C      WRITE(25,9)
03800 C      9 FORMAT(7X,'TBULK',8X,'TWALL',8X,'TMI',8X,'PRESS',8X,'AREAE'
03900 C      1,8X,'ALENG',8X,'QEXLH',8X,'HCOEF',8X,'REY')
04000 C      DC IS THE DIAMETER OF THE TUBE COIL
04100 C      DC=15.0
04200 C      PA=P-0.1
04300 C      CALL PROP(THEM1,P,ENT3,3)
04310 C      CALL PROP(THEM1,PA,ENT4,3)
04320 C      QMEX=AM*(ENT4-ENT3)
04400 C      101 CONTINUE

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```

04600      CALL PROP(THEM2,PA,ENT2,3)
04700      CALL PROP(THEM1,PA,ENT1,3)
04800      QME=AM*(ENT2-ENT1)+QMEX
05000      120 IF(QME-QM)100,140,150
05100      100 THEM1=THEM1+TINT
05200      THEM2=THEM2+TINT
05300      QMEX=QME
05400      GO TO 101
05500      140 TMD=THEM2
05550      C      TMD IS THE TEMPERATURE OF THE STREAM ENTERING THE
05551      C      COUNTERCURRENT EXCHANGER
05600      C      GO TO 160
05700      150 TMD=TINT*(QM-QMEX)/(QME-QMEX + THEM1)
05800      160 CONTINUE
05900      C      TEMP IS THE TEMPERATURE EXITING THE CALCULATION
06000      C      INCREMENT.
06100      170 TEMP=THI
06200      C      TWI IS THE INSIDE WALL TEMPERATURE IN THE CALCULATION
06300      C      INCREMENT
06400      TWI=THI
06500      C      AREAE IS THE CUMULATIVE AREA FOR HEAT TRANSFER
06600      AREAE=0
06700      C      PDROP IS THE CUMULATIVE PRESSURE DROP
06800      PDROP=0
06900      GO TO 100
07000      171 TEMP=TEMP + TINT
07100      C      THIS SECTION CALCULATES THE ENERGY BALANCE FOR
07200      C      EACH CALCULATION INCREMENT. THE METHOD FOR THIS IS
07300      C      TO ASSUME A TEMPERATURE DROP IN THE EXCHANGER,
07400      C      AND CALCULATE THE AREA NEEDED TO ACCOMPLISH THAT
07500      C      TEMPERATURE DROP. PROPERTIES FOR THE CALCULATION
07600      C      INCREMENT ARE BASED ON THE AVERAGE TEMPERATURE AND
07700      C      PRESSURE IN THE INCREMENT.
07800      C      TBULK IS THE BULK FLUID TEMPERATURE
07900      180 TBULK =TEMP+(0.5*TINT)
08000      C      TEMP2 IS THE ENTRANCE TEMPERATURE TO THE CALC. INCREMENT
08100      TEMP2=TEMP+TINT
08300      C      PRESS IS THE PRESSURE IN THE CALC. INCREMENT.
08400      PRESS=PDROP + P
08405      K=0
08410      PRES2=PRESS
08415      PRES3=PRESS
08420      226 CONTINUE
08422      K=K+1
08425      TWIH=TWI
08500      190 CALL PROP(TBULK,PRES3,AMYU,1)
08600      C      REY IS THE REYNOLDS NUMBER IN THE CALC. INCREMENT
08700      200 REY=4*AM/(3.14*ADIAM*AMYU)
08800      210 CALL PROP(TBULK,PRES3,PRAD,4)
08900      C      ANUSS IS THE MUSSELT NUMBER IN THE CALC. INCREMENT
09000      220 ANUSS=0.023*(REY**0.8)*(PRAD**0.4)
09100      230 CALL PROP(TBULK,PRES3,CONDK,6)
09200      C      HCOEF IS THE INSIDE HEAT TRANSFER COEFFICIENT
09300      240 HCOEF= ANUSS * CONDK / ADIAM
09600      CALL PROP(TEMP2,PRES2,ENTH2,3)
09700      CALL PROP(TEMP,PRESS,ENTH1,3)
09800      C      QEXLH IS THE HEAT LOSS TO THE BATH IN CALC. INCREMENT
09900      QEXLH=AM*(ENTH2-ENTH1)
10100      C      ADIFF IS THE TEMPERATURE DIFFERENCE BETWEEN THE
10200      C      WALL AND BATH. IT IS USED TO DETERMINE THE BOILING
10300      C      HEAT TRANSFER COEFFICIENT
10350      M=0
10400      270 ADIFF=TWALL-THE
10425      M=M+1
10450      TAAVE=(TWI+TWALL)/2.0

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10500      200 IF (ADIFF-0.45) 290,300,300
10600      C      CKON AND CKONA ARE CONSTANTS IN THE BOILING HEAT
10700      C      TRANSFER MODEL, Q/A=CKON*(TWALL-THE)**CKONA
10800      290 CKON=6.74
10900          CKONA=2.39
11000          GO TO 329
11100      300 CKON=0.024
11200          CKONA=1.19
11300      C      THIS SECTION USES THE NEWTON-RAPHSON METHOD TO
11400      C      CALCULATE THE OUTSIDE WALL TEMPERATURE
11500      329 CALL PROP(TAWE,PRES3,CLK,7)
11600      330 TWALL=TWI-(HCOEF*(TBULK-TWI)*ALOG(DIAM/ADIAM)*ADIAM)/(2*CLK)
11700      330 ART=CKON*DIAM*(TWALL-THE)**CKONA-HCOEF*ADIAM*(TBULK-TWI)
11800      330 VARI=CLK/(ALOG(DIAM/ADIAM)*ADIAM/2)
11900      330 VARIA=VARI/(HCOEF+VARI)
12000      330 CART=CKON*DIAM*CKONA*(TWALL-THE)**(CKONA-1)+HCOEF*ADIAM*VARIA
12100      331 TFIND=TWALL-ART/CART
12200      331 KFIN=TFIND*100
12300      331 KWALL=TWALL*100
12400      331 IF (K-100) 339,343,343
12500      339 IF (KFIN-KWALL) 340,343,340
12600      340 TWALL = TFIND
12700      340 TWI=(VARI*TWALL+HCOEF*TBULK)/(HCOEF+VARI)
12800      340 GO TO 270
12900      343 CONTINUE
13000      C      THIS SECTION CALCULATES THE AREA NEEDED TO TRANSFER
13100      C      THE DESIRED AMOUNT OF HEAT FROM THE CALC. INCREMENT
13200      350 AREA=(QEXLH/(HCOEF*(TBULK-TWI)))
13300      C      THIS SECTION CALCULATES THE PRESSURE DROP IN THE
13400      C      CALCULATION INCREMENT.
13500      360 FRICT=0.08/(REY**0.25)+0.01*(ADIAM/DC)**0.5
13600      360 CALL PROP(TBULK,PRES3,RO,2)
13700      360 CALL PROP(TEMP,PRES3,ROUT,2)
13800      360 CALL PROP(TEMP2,PRES2,ROIN,2)
13900      370 VEL=AM**4/(RO**3.14*ADIAM**2.0)
14000      370 VELI=(AM**4.0)/(ROIN**3.14*ADIAM**2.0)
14100      370 VELO=(AM**4.0)/(ROUT**3.14*ADIAM**2.0)
14200      370 ALENG=AREA/(3.14*ADIAM)
14300      380 DRO=PDROP+(2*FRICT*VEL**2.0*RO*ALENG*(9.87*10**(-7.0))/ADIAM)
14400      380 I-RO*VEL*(VELI-VELO)*(9.87*10**(-7.0))
14500      380 PRES4=PRES2
14600      380 PRES2=DRO+P
14700      380 PRES3=PRES+(PRES2-PRES)/2.0
14800      380 IF (K-100) 401,400,400
14900      401 IF (K-2) 390,399,399
15000      399 KENT4=5000*PRES4
15100      399 KENT2=5000*PRES2
15200      399 KENT5=100*TWI
15300      399 KENT6=100*TWI/H
15400      399 IF (KENT6-KENT5) 226,397,226
15500      397 IF (KENT4-KENT2) 226,400,226
15600      390 GO TO 226
15700      400 CONTINUE
15800      C      CHECK TO SEE IF THE TEMPERATURE IS WITHIN THE
15900      C      DESIRED EXCHANGER INLET TEMPERATURE
16000      AREAE=AREA+AREAE
16100      PDROP=DRO
16200      390 TDROP=TEMP2-TMO
16300      390 WRITE(25,8)TBULK,TWALL,TWI,PRES,AREAE,ALENG,QEXLH,HCOEF,REY
16400      8 FORMAT(8F13.5,F13.0)
16500      ZPRES=PRES2
16600      ZLENG=AREAE/(314.159*ADIAM)
16700      QTOT=QTOT+QEXLH
16800      IF (TDROP-TINLT)171,410,410
16900      410 WRITE (25,420) TMI,P,TEMP2,ZPRES,AREAE,ZLENG,QTOT,ADIAM,DIAM,TMO
17000      420 FORMAT(//,' INLET TEMP. TO MAGNET ','F10.2',' K',//,

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17000 1' INLET PRESS. TO MAGNET =',F10.3,' ATM',,,,
17100 2' INLET TEMP. TO EXCHANGER =',F10.2,' K',,,,
17200 3' INLET PRESS. TO EXCHANGER =',F10.3,' ATM',,,,
17300 4' TOTAL AREA OF HEAT TRANSFER =',F15.3,' SQ. CM',,,,
17400 5' LENGTH OF EXCHANGER =',F10.5,' METERS',,,,
17500 6' TOTAL HEAT TRANSFERRED =',F20.3,' WATTS',,,,
17600 7' INSIDE DIAMETER OF TUBE =',F10.6,' CM',,,,
17700 8' OUTSIDE DIAMETER OF TUBE =',F10.6,' CM',,,,
17750 9' TEMP FROM MAGNET=',F10.4,' K',,,,
17800 TYPE 420,TM1,P,TEMP2,ZPRES,AREAE,ZLENG,QTDT,AD:AM,DIAM
17900 TYPE 900,TM0
18000 900 FORMAT(' TEMP FROM MAG',F10.4)
18100 CALL EXIT

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10.1.2 Countercurrent Exchanger

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00010 C      THIS PROGRAM IS USED TO DESIGN THE COUNTER CURRENT
00015 C      HEAT EXCHANGER FOR THE COOLING OF THE HELIUM STREAM
00020 C      FROM THE NITROGEN BATH HEAT EXCHANGER.
00025 C      THE METHOD EMPLOYED IS TO SPECIFY CONDITIONS AT THE
00030 C      BOTTOM OF THE EXCHANGER AND TO BACK CALCULATE UP THE
00035 C      EXCHANGER BY SMALL TEMPERATURE INCREMENTS UNTIL
00040 C      THE DESIRED INLET TEMPERATURE IS FOUND.
00045 C      PRESSURE AND TEMPERATURE PROFILES ARE OBTAINED AND
00050 C      THE LENGTH OF EXCHANGER NEEDED ARE OUTPUT.
00051
00052
00053 WRITE(25,363)
00061 363 FORMAT(' TUBE PRESSURE',T12,' TUBE TEMP',T24,' SHELL PRESS.',
00062          1T36,' SHELL TEMP.',/,,'ATM',T12,'K',T24,'ATM',T36,'K',
00063          1T40,'RENO',T60,'RENI',T72,'QINC',T84,'VELI',T96,'VELO',/)
00095 C      PII IS THE EXIT PRESSURE FROM THE COUNTER CURRENT
00096 C      EXCHANGER GOING TO THE HELIUM BATH EXCHANGER
00100 C      PII=4.006
00102 C      HEAT EXCHANGER COVERED BY THE CALCULATION
00103 C      AKEI IS THE CUMULATIVE AREA FOR HEAT TRANSFER
00105
00120 C      QDOT=0.8
00150 C      AKEI=0
00195 C      POO IS THE INLET PRESSURE TO THE MAGNET TEST SECTION
00200 C      POO=4.0
00205 C      POF IS THE SHELLSIDE INLET PRESSURE TO THE COUNTER
00206 C      CURRENT EXCHANGER
00210 C      POF=POO-.1
00245 C      DIAMI IS THE INSIDE DIAMETER OF THE TUBE IN THE
00246 C      COUNTER CURRENT EXCHANGER
00250 C      DIAMI=.5
00255 C      DIAMR IS THE INSIDE DIAMETER OF THE SHELL IN THE
00256 C      COUNTER CURRENT EXCHANGER
00260 C      DIAMR=1.1
00265 C      DIAMO IS THE OUTSIDE DIAMETER OF THE TUBE IN THE COUNTER
00266 C      CURRENT EXCHANGER
00270 C      DIAMO=.635
00275 C      HYRA IS THE HYDRAULIC RADIUS
00280 C      HYRA=(DIAMR-DIAMO)/4.0
00290 C      AM IS THE MASS FLOW RATE OF THE HELIUM
00300 C      AM=1.0
00310 C      DROPI=0
00311 C      DC IS THE COIL DIAMETER
00312 C      DC=15.0
00315 C      DROPI IS THE TUBESIDE PRESSURE DROP IN THE
00316 C      COUNTER CURRENT HEAT EXCHANGER.
00317 C      DROPO IS THE SHELLSIDE PRESSURE DROP IN THE
00318 C      COUNTER CURRENT HEAT EXCHANGER
00320 C      DROPO=0
00330 C      PO=POF
00340 C      PI=PII
00341
00342 C      THIS SECTION OF THE PROGRAM CALCULATES THE ENERGY
00343 C      BALANCE AROUND A CALCULATION INCREMENT OF EXCHANGER
00344 C      THE PROGRAM ASSUMES THE CONDITIONS AT THE BOTTOM
00345 C      OF THE COUNTER CURRENT EXCHANGER AND BACKSTEPS
00346 C      UP THE EXCHANGER, CALCULATING TEMPERATURE INCREMENTS,
00347 C      UNTIL THE TUBESIDE TEMPERATURE IS EQUAL TO 80 DEGREES
00348 C      KELVIN
00349

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00350 C      THO IS THE OUTLET TEMPERATURE FROM THE MAGNET
00400 1020 THO=19.0944
00450 C      TBULK IS THE INLET TEMPERATURE TO THE HELIUM BATH
00451 C      HEAT EXCHANGER
00500 1030 TBULK=23.1
00540 C      TODA IS THE EXIT TEMPERATURE FROM A CALCULATION
00541 C      INCREMENT IN THE TUBE
00550 TODA=TBULK
00575 C      TINTV IS THE TEMPERATURE INCREMENT FOR CALCULATIONS
00600 1040 TINTV=0.5
00650 TAB=THO
00675 C      TAVEO IS THE SHELLSIDE AVERAGE TEMP IN A CALC. INCREMENT
00700 TAVEO=(TINTV*0.5) + THO
00800 GO TO 1060
00930 1050 TAVEO=TAEO+(TINTV*0.5)
00950 TODA=TCOMP1
00960 TAB=TAEO
00965 1060 PO=POF-DROPO
00966 PI=PII+DROPI
00967 PMAY=PO
00968 PLAST=PI
00970 TABO=TAB+TINTV
00972 L=0
00973 77 CONTINUE
00974 IF (L-100) 78,70,351
00975 70 L=L+1
00976 IF (TAB-29.7) 27,28,28
00980 28 CALL PROP(TAVEO,PO,CAPHE,5)
00985 QHTRM=AM*CAPHE*TINTV
00990 GO TO 2021
00995 27 CONTINUE
01010 CALL PROP(TAB,PO,EN1,3)
01016 CALL PROP(TABO,PMAY,EN2,3)
01017 C      QHTRM IS THE HEAT GAINED BY THE SHELLSIDE
01018 QHTRM=AM*(EN2-EN1)
01019 2021 IF (TODA-29.7) 96,97,97
01020 96 CALL PROP(TODA,PI,E1,3)
01040 E2=E1+QHTRM/AM
01041 CALL PROP(4.0,PLAST,E01,3)
01042 CALL PROP(4.5,PLAST,E02,3)
01043 CALL PROP(5.0,PLAST,E03,3)
01044 CALL PROP(5.5,PLAST,E04,3)
01045 CALL PROP(6.0,PLAST,E05,3)
01046 CALL PROP(7.0,PLAST,E06,3)
01047 CALL PROP(10.0,PLAST,E07,3)
01048 CALL PROP(15.0,PLAST,E08,3)
01049 CALL PROP(16.0,PLAST,E09,3)
01050 CALL PROP(20.0,PLAST,E10,3)
01051 CALL PROP(30.0,PLAST,E11,3)
01001 IF (E02-E2) 2000,2011,2011
01002 2000 IF (E03-E2) 2001,2012,2012
01003 2001 IF (E04-E2) 2002,2013,2013
01004 2002 IF (E05-E2) 2003,2014,2014
01005 2003 IF (E06-E2) 2004,2015,2015
01006 2004 IF (E07-E2) 2005,2016,2016
01007 2005 IF (E08-E2) 2006,2017,2017
01008 2006 IF (E09-E2) 2007,2018,2018
01009 2007 IF (E10-E2) 2008,2019,2019
01090 2011 TCOMP1=4.0+(0.5*(E2-E01)/(E02-E01))
01091 GO TO 2020

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01092 2012 TCOMP=4.5+(0.5*(E2-E02)/(E03-E02))
01093 GO TO 2020
01094 2013 TCOMP=5.0+(0.5*(E2-E03)/(E04-E03))
01095 GO TO 2020
01096 2014 TCOMP=5.5+((E2-E04)/(E05-E04))
01097 GO TO 2020
01098 2015 TCOMP=6.0+((E2-E05)/(E06-E05))
01099 GO TO 2020
01100 2016 TCOMP=7.0+(3.0*(E2-E06)/(E07-E06))
01101 GO TO 2020
01102 2017 TCOMP=10.0+(5.0*(E2-E07)/(E08-E07))
01103 GO TO 2020
01104 2018 TCOMP=15.0+((E2-E08)/(E09-E08))
01105 GO TO 2020
01106 2019 TCOMP=16.0+(4.0*(E2-E09)/(E10-E09))
01107 GO TO 2020
01108 2000 TCOMP=20.0+(10.0*(E2-E10)/(E11-E10))
01109 2020 TCOMP=(TCOMP+T00A)/2.0
01120 GO TO 1090
02000 97 TCOMP=T00A
02050 TAAA=T00A
02075 M=0
02100 98 CALL PROP(TCOMP,PI,CAPH,5)
02101 M=M+1
02102 TIN=QWTRM/(AM*CAPH)
02103 TCOMP=T00A+0.5*TIN
02104 IS=100*TCOMP
02105 ISS=100*TAAA
02106 IF (IS-ISS) 99,3000,99
02107 99 TAAA=TCOMP
02108 IF (M-100) 80,80,3000
02109 80 GO TO 98
02200 3000 TCOMP=T00A+TIN
02300
02390 C DELTT IS THE TEMPERATURE DIFFERENCE BETWEEN THE
02391 C TUBESIDE AVERAGE TEMP AND THE SHELLSIDE AVERAGE TEMP
02400 1090 DELTT=TCOMP-TAVEO
02460 POAVE=(PO+PMAY)/2.0
02470 PIAVE=(PI+PLAST)/2.0
02500 CALL PROP(TAVEO,POAVE,UM,1)
02550 C RENO IS THE SHELLSIDE REYNOLDS NUMBER
02600 RENO=4*AM/(3.14*UM*(DIAMR+DIAMD))
02700 CALL PROP(TCOMP,PIAVE,UM,1)
02750 C RENI IS THE TUBESIDE REYNOLDS NUMBER
02800 RENI=4*AM/(3.14*UM*DIAMI)
02900 CALL PROP(TAVEO,PGAVE,DARP,4)
02950 C ANUSO IS THE SHELLSIDE NUSSELT NUMBER
02960 IF (TAVEO-30.0) 902,900,900
02970 902 IF (L-2) 900,905,905
03000 900 ANUSO=0.023*(RENO**0.8)*(DARP**0.4)
03010 GO TO 910
03020 905 ANUSO=0.0259*(RENO**0.8)*(DARP**0.4)*((TAVEO/TWALL)**0.716)
03100 910 CALL PROP(TCOMP,PIAVE,DARPI,4)
03150 C ANUSI IS THE TUBESIDE NUSSELT NUMBER
03160 IF (TCOMP-30.0) 904,915,915
03170 904 IF (L-2) 915,920,920
03200 915 ANUSI=0.023*(RENI**0.8)*(DARPI**0.4)
03210 GO TO 925
03220 920 ANUSI=0.0259*(RENI**0.8)*(DARPI**0.4)*((TCOMP/TWI)**0.716)
03300 925 CALL PROP(TAVEO,POAVE,UCONO,6)

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03350 C      HCO IS THE SHELLSIDE HEAT TRANSFER COEFFICIENT
03400      HCO=ANUSO*UCONO/(HYRA*4.0)
03500      CALL PROP(TCOMP,PIAVE,UCONI,6)
03550 C      HCI IS THE TUBESIDE HEAT TRANSFER COEFFICIENT
03600      HCI=ANUSI*UCONI/DIAM1
03625 C      RES1,RES2,RES3 ARE THE RESISTANCES DUE TO THE
03626 C      THE TUBESIDE HEAT TRANSFER COEFFICIENT, THE THERMAL
03627 C      CONDUCTIVITY OF THE WALL, AND THE SHELLSIDE HEAT
03628 C      TRANSFER COEFFICIENT, RESPECTIVELY.
03629      IF (L-2) 930,935,935
03630 930 TAVER=(TAVEO+TCOMP)/2.0
03635 935 PCON=(PIAVE+POAVE)/2.0
03640      CALL PROP(TAVER,PCON,CUK,7)
03650      RES1=1/(HCI*DIAM1)
03660      RES2=1/(HCO*DIAM0)
03670      RES3=ALOG(DIAM0/DIAM1)/(2*CUK)
03700      HOVER=1/(RES1+RES2+RES3)/DIAM1
03800      ARE = QHTRM/(HOVER*DELTT)
03910      TWI=TCOMP-(QHTRM/(ARE*HCI))
03920      TWALL=QHTRM/(ARE*(DIAM0/DIAM1)*HCO)+TAVEO
03930      TAVER=(TWALL+TWI)/2.0
03950 C      GNEL IS THE LENGTH OF THE CALC. INCREMENT
04000      GNEL=ARE/(3.14*DIAM1)
04050 C      FRICI IS THE TUBESIDE FRICTION FACTOR
04100      FRICI=0.08/(RENI**0.25)+0.01*(DIAM1/DC)**0.5
04150 C      FRICO IS THE SHELLSIDE FRICTION FACTOR
04200      FRICO=0.08/(RENO**0.25)+0.01*((4.0*HYRA)/DC)**0.5
04210      IF (TCOMP-50.0) 950,951,951
04220 951 RO1=PIAVE/(20.515*TCOMP)
04230      RO11=PI/(20.515*TOOA)
04240      RO12=PLAST/(20.515*TCOMP1)
04250      GO TO 955
04300 950 CALL PROP(TCOMP,PIAVE,RO1,2)
04310      CALL PROP(TOOA,PI,RO11,2)
04320      CALL PROP(TCOMP1,PLAST,RO12,2)
04350 C      VELI IS THE TUBESIDE LINEAR VELOCITY
04400 955 VELI=4.0*AM/(RO1*3.14*(DIAM1**2.0))
04410      VEL11=4.0*AM/(RO11*3.14*(DIAM1**2.0))
04420      VEL12=4.0*AM/(RO12*3.14*(DIAM1**2.0))
04450      IF (TAVEO-50.0) 952,953,953
04460 953 ROO=POAVE/(20.515*TAVEO)
04470      ROO1=PO/(20.515*TAB)
04480      ROO2=PMAY/(20.515*TABO)
04490      GO TO 954
04500 952 CALL PROP(TAVEO,POAVE,ROO,2)
04510      CALL PROP(TAB,PO,ROO1,2)
04520      CALL PROP(TABO,PMAY,ROO2,2)
04550 C      VELO IS THE SHELLSIDE LINEAR VELOCITY
04600 954 VELO=4*AM/(ROO*3.14*(DIAMR**2-DIAMD**2))
04510      VELO1=4.0*AM/(ROO1*3.14*(DIAMR**2-DIAMD**2.0))
04620      VELO2=4.0*AM/(ROO2*3.14*(DIAMR**2-DIAMD**2.0))
04700      DRI=DRO1+(2*RO1*GNEL*FRICI*VELI**2*(9.87E-7)/DIAM1)
04701      I-RO1*VELI*(VEL12-VEL11)*(9.87E-7)
04799      DRO=DROD+(ROO*GNEL*FRICO*(VELO**2.0)*(9.87E-7)/(2.0*HYRA))
04800      I+ROO*VELO*(VELO2-VELO1)*(9.87E-7)
04801      PYAM=PMAY
04802      PTSAL=PLAST
04803      PLAST=PII+DRI
04804      PMAY=POF-DRO
04805      IF (L-2) 77,1055,1055

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04006 1055 IF (TAB-29.7) 900.06,06
04007 900 CALL PROP(TAB,PAY,EH!,3)
04008 KEN1=EH1*10
04009 KEN2=EN2*10
04010 IF (KEN2-KEN1) 77.06,77
04016 86 IF (TDA-29.7) 87.907,907
04018 87 CALL PROP(TCOMPI,PLAST,ELAST,3)
04019 KLAST=ELAST*10
04021 KEI=(EI+QHTRM/AM)*10
04022 IF (KEI-KLAST) 77.907,77
04023 907 CONTINUE
04024 KLASTC=PLAST*5000
04025 KPAYC=PAY*5000
04027 KLASTB=PLAST*5000
04028 KPAYB=PAY*5000
04029 IF (KLASTB-KLASTC) 77.350,77
04038 350 IF (KPAYB-KPAYC) 77.351,77
04031 351 AREI=ARE+AREI
04033 DROI=DRI
04034 DROPO=DRO
04035 PRESI=PII+DROI
04036 ZLENG=AREI/(3.14159*100.0*DIAMI)
04037 PRESO=POF-DROPO
04038 QTOT=QTOT+QHTRM
04039
04050 C IF THE ENTRANCE TEMPERATURE TO THE TUBE CALC. INCREMENT
04051 C IS 80 DEGREES KELVIN, OUTPUT
04074 WRITE(25,400) PRESI,TCOMP,PRESO,TAVEO,RENO,RENI,QHTRM,
04075 1VELI,VELO
04076 400 FORMAT(F10.3,T12,F10.3,T24,F10.3,T36,F10.3,T40,F10.0,T60,
04077 F10.0,T72,F10.3,T84,F10.0,T96,F10.0)
04080 IF (TCOMP-80.0) 1050,1400,1400
05000 1400 TYPE 364,DROPO,DROI,AREI,ZLENG
05001 WRITE(25,364) DROPO,DROI,AREI,ZLENG
05010 TYPE 362,TCOMP,PRESI
05011 WRITE(25,362) TCOMP,PRESI
05110 362 FORMAT(' INLET TUBE TEMP =',F10.3,/,
05210 1' INLET PRESSURE =',F10.3,/,
05500 364 FORMAT('//////, SHELLSIDE PRESSURE DROP =',F20.5,' ATM',/,
05600 1' TUBESIDE PRESSURE DROP =',F20.5,' ATM',/,
05700 2' AREA OF HEAT TRANSFER =',F20.5,' SQ. CM',/,
05800 3' LENGTH OF EXCHANGER =',F20.5,' METERS')
05850 TYPE 365,DIAMI,DIAMO,DIAMR,AM,TMO,TBULK
05855 365 FORMAT('//, INSIDE DIAMETER OF TUBE =',F10.5,' CM',/,
05856 1' OUTSIDE DIAMETER OF THE TUBE =',F10.5,' CM',/,
05857 2' INSIDE DIAMETER OF THE SHELL =',F10.5,' CM',/,
05858 3' MASS FLOW RATE =',F10.5,' GRAMS/SEC',/,
05859 4' TEMP. OF SHELLSIDE STREAM ENTERING EXCHANGER =',F10.5,' K',/,
05860 5' TEMP. OF TUBESIDE STREAM EXITING EXCHANGER =',F10.5,' K',/)
05865 WRITE(25,366) QTOT
05870 TYPE 366,QTOT
05880 366 FORMAT(' TOTAL HEAT LOSS FROM TUBE TO SHELL =',F10.3,' WATTS')
05882 WRITE(25,367) PII,TMO,TBULK,AM
05884 367 FORMAT('//, OUTLET TUBE PRESSURE =',F10.5,' ATM',/,
05886 1' INLET SHELL TEMPERATURE =',F10.5,' K',/,
05888 2' OUTLET TUBE TEMPERATURE =',F10.5,' K',/,
05900 3' MASS FLOW RATE =',F10.5,' GRAMS/SEC',/)
05900 CALL EXIT
06000 END

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10.1.3 Nitrogen Bath Exchanger

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00005 C      THIS PROGRAM IS USED TO DESIGN THE LIQUID NITROGEN
00006 C      BATH HEAT EXCHANGER.  THE GENERAL METHOD OF CALCULATION
00007 C      IS BY SPECIFYING THE CONDITIONS DESIRED GOING
00008 C      INTO THE COUNTER CURRENT EXCHANGER.  THE PROGRAM BACKSTEPS
00009 C      UNTIL THE TEMPERATURE AT THE INLET TO THE EXCHANGER
00010 C      IS WITHIN SOME TEMPERATURE OF THE MAGNET EXIT STREAM
00011 C      THE AREA, LENGTH, AND PRESSURE DROP ENCOUNTERED IN THE
00012 C      EXCHANGER ARE THEN OUTPUTED.  PROFILES OF THE TEMPERATURES
00013 C      ARE GIVEN.
00019 C      P IS THE PRESSURE AT THE EXIT OF THE EXCHANGER
00020 C      P=7.008
00103 C      TMI IS THE OUTLET TEMPERATURE OF THE EXCHANGER
00104 C      TMI=80.472
00107 C      TINT IS THE INCREMENT OF TEMPERATURE FOR EACH SECTION
00108 C      TINT=1.0
00111 C      AM IS THE FLOW RATE OF THE HELIUM (GRAMS/SEC)
00112 C      AM=5.0
00115 C      ADIAM IS THE INSIDE TUBE DIAMETER (CM)
00116 C      ADIAM=.5
00119 C      DIAM IS THE OUTSIDE TUBE DIAMETER (CM)
00120 C      DIAM=.635
00123 C      THE IS THE LIQUID NITROGEN BATH TEMPERATURE
00124 C      THE=77.0
00156 C      WRITE(25,5)
00160 C      9 FORMAT(7X,'TBULK',8X,'TWALL',8X,' TWI',8X,'PRESS',8X,'VELOCITY'
00164 C      1,8X,'ALENG',8X,'QEXLH',8X,'HCOEF',8X,'REY')
00095 C      TEMP IS THE TEMPERATURE EXITING THE CALCULATION
00096 C      INCREMENT.
00099 C      170 TEMP=TWI
00099 C      TWI IS THE INSIDE WALL TEMPERATURE IN THE CALCULATION
00096 C      INCREMENT
00099 C      TWI=TWI
00099 C      TWALL IS THE OUTSIDE WALL TEMPERATURE IN THE CALCULATION
00099 C      INCREMENT
00099 C      TWALL=TWI
00095 C      AREAE IS THE CUMULATIVE AREA FOR HEAT TRANSFER
00099 C      AREAE=0
00095 C      PDROP IS THE CUMULATIVE PRESSURE DROP
00099 C      PDROP=0
00099 C      QTOT IS THE ACCUMULATIVE HEAT LOST THROUGH THAT PORTION OF
00099 C      HEAT EXCHANGER COVERED BY THE CALCULATION
00099 C      QTOT=0.0
00099 C      M=0
00099 C      GO TO 180
00099 C      171 TEMP=TEMP + TINT
00099 C      M=M+1
00099 C      THIS SECTION CALCULATES THE ENERGY BALANCE FOR
00099 C      EACH CALCULATION INCREMENT.  THE METHOD FOR THIS IS
00099 C      TO ASSUME A TEMPERATURE DROP IN THE EXCHANGER,
00099 C      AND CALCULATE THE AREA NEEDED TO ACCOMPLISH THAT
00099 C      TEMPERATURE DROP.  PROPERTIES FOR THE CALCULATION
00099 C      INCREMENT ARE BASED ON THE AVERAGE TEMPERATURE IN
00099 C      THE INCREMENT.
00099 C      TBULK IS THE BULK FLUID TEMPERATURE
00099 C      180 TBULK =TEMP+(0.5*TINT)
00099 C      TEMP2 IS THE ENTRANCE TEMPERATURE TO THE CALC. INCREMENT
00099 C      TEMP2=TEMP+TINT
00099 C      PRESS IS THE PRESSURE IN THE CALC. INCREMENT.
00099 C      PRESS=PDROP + P
00099 C      PST=PRESS

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01560      PP2=PRESS
01570      189 CONTINUE
01580      M=M+1
01600      190 CALL PROP(TBULK,PST,AMU,1)
01695      C      REY IS THE REYNOLDS NUMBER IN THE CALC. INCREMENT
01700      200 REY=4*AM/(3.14*ADIAM*AMU)
01800      210 CALL PROP(TBULK,PST,PRAD,4)
01850      C      ANUSS IS THE NUSSELT NUMBER IN THE CALC. INCREMENT
01900      220 ANUSS=0.023*(REY**0.8)*(PRAD**0.4)
02000      230 CALL PROP(TBULK,PST,CONDK,6)
02050      C      HCOEF IS THE INSIDE HEAT TRANSFER COEFFICIENT
02100      240 HCOEF=ANUSS*CONDK/ADIAM
02200      CALL PROP(TBULK,PST,CAP1,5)
02295      C      QEXLH IS THE HEAT LOSS TO THE BATH IN CALC. INCREMENT
02300      QEXLH=AM*CAP1*(TEMP2-TEMP)
02355      C      ADIFF IS THE TEMPERATURE DIFFERENCE BETWEEN THE
02360      C      WALL AND BATH. IT IS USED TO DETERMINE THE BOILING
02365      C      HEAT TRANSFER COEFFICIENT
02390      K=0
02400      270 ADIFF=TWALL-THE
02410      K=K+1
02450      TST=(TWI+TWALL)/2.0
02500      280 IF (ADIFF-11.0) 290,300,300
02550      C      CKON AND CKONA ARE CONSTANTS IN THE BOILING HEAT
02555      C      TRANSFER MODEL. Q/A=CKON*(TWALL-THE)**CKONA
02600      290 CKON=0.0527
02700      CKONA=2.44
02800      GO TO 329
03400      300 CKON=0.026
03500      CKONA=0.9
03620      C      THIS SECTION USES THE NEWTON-RAPHSON METHOD TO
03621      C      CALCULATE THE OUTSIDE WALL TEMPERATURE
03625      329 CALL PROP(TST,PST,CUK,7)
03650      330 TWALL=TWI-(HCOEF*(TBULK-TWI)*ALOG(DIAM/ADIAM)*ADIAM/(2*CUK)
03700      ART=CKON*DIAM*(TWALL-THE)**CKONA-HCOEF*ADIAM*(TBULK-TWI)
03750      VARI=CUK/(ALOG(DIAM/ADIAM)*ADIAM/2)
03754      VARIA=VARI/(HCOEF+VARI)
03800      CART=CKON*DIAM*CKONA*(TWALL-THE)**(CKONA-1)+HCOEF*ADIAM*VARIA
03900      331 TFIND=TWALL-ART/CART
04000      KFIND=TFIND*100
04100      KWALL=TWALL*100
04150      IF (K-100) 339,343,343
04200      339 IF (KFIND-KWALL) 340,343,340
04250      340 TWALL = TFIND
04351      TWI=(VARI*TWALL+HCOEF*TBULK)/(HCOEF+VARI)
04400      GO TO 270
04410      343 CONTINUE
04450      C      THIS SECTION CALCULATES THE AREA NEEDED TO TRANSFER
04451      C      THE DESIRED AMOUNT OF HEAT FROM THE CALC. INCREMENT
04500      350 AREA=(QEXLH/(HCOEF*(TBULK-TWI)))
04550      ALENG=AREA/(3.14*ADIAM)
04580      C      THIS SECTION CALCULATES THE PRESSURE DROP IN THE
04581      C      CALCULATION INCREMENT.
04600      360 FRICT=0.079/(REY**0.25)
04650      R0=PST/(20.515*TBULK)
04700      R022=PP2/(20.515*TEMP2)
04720      R011=PRESS/(20.515*TEMP)
04730      VEL1=(AM*4.0)/(R011*3.14*(ADIAM**2.0))
04740      VEL2=(AM*4.0)/(R022*3.14*(ADIAM**2.0))
04800      370 VEL=AM*4/(R0*3.14*(ADIAM**2.0))

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05009 380 PDRO=(2.0*FRICT*(VEL**2.0)*RO*ALENG*(9.87*(10**(-7.0)))/ADIAM)
05011 1-RO*VEL*(VEL2-VEL1)*9.87*(10**(-7.0))
05013 C CHECK TO SEE IF THE TEMPERATURE IS WITHIN THE
05015 C DESIRED EXCHANGER INLET TEMPERATURE
05017 PCHECK=PP2
05019 PP2=PRESS+PDRO
05021 PST=(PP2+PRESS)/2.0
05023 IHOPE=5000*PCHECK
05025 IWOND=5000*PP2
05027 IF (M-130) 401,385,385
05029 401 IF (M-2) 189,386,386
05031 386 IF (IHOPE-IWOND) 189,385,189
05033 385 PDROP=PDRO+PDROP
05035 AREAE=AREA+AREAE
05037 WRITE(25,8) TBULK, TWALL, TWI, PRESS, VEL, ALENG, QEXLH, HCOEF, REY
05039 8 FORMAT(9F13.5)
05041 ZPRES=PP2
05043 ZLENG=AREAE/(314.159*ADIAM)
05045 QTOT=QTOT+QEXLH
05047 IF (TBULK-298.0) 171,410,410
05049 419 WRITE(25,420) TMI,P,TBULK,ZPRES,AREAE,ZLENG,QTOT,ADIAM,DIAM,AM
05051 TYPE 420,TMI,P,TEMP2,ZPRES,AREAE,ZLENG,QTOT,ADIAM,DIAM
05053 420 FORMAT(//,' EXCHANGER EXIT TEMPERATURE =',F10.2,' K',//,
05055 1' EXCHANGER EXIT PRESSURE =',F10.3,' ATM',//,
05057 2' INLET TEMP. TO EXCHANGER =',F10.2,' K',//,
05059 3' INLET PRESS. TO EXCHANGER =',F10.3,' ATM',//,
05061 4' TOTAL AREA OF HEAT TRANSFER =',F15.3,' SQ. CM',//,
05063 5' LENGTH OF EXCHANGER =',F10.5,' METERS',//,
05065 6' TOTAL HEAT TRANSFERRED =',F20.3,' WATTS',//,
05067 7' INSIDE DIAMETER OF TUBE =',F10.6,' CM',//,
05069 8' OUTSIDE DIAMETER OF TUBE =',F10.6,' CM',//,
05071 9' MASS FLOW RATE =',F10.6,' GRAMS/SEC',//)
05073 TYPE 900,VEL
05075 900 FORMAT(' YOU MADE IT TO HERE!',F10.3)
05077 CALL EXIT
05079 END

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

FLOW CHART FOR NITROGEN BATH
HEAT EXCHANGER COMPUTER PROGRAM

DATE
10-24-76

DRAWN BY
REB

FILE NO.
CFPS-X-242

FIG.
10d

10.1.4 Helium Properties Subroutine

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SUBROUTINE PROP(TEMP,PRESS,ZPROP,J)

C
C   THIS SUBROUTINE IS FOR THE CALCULATION OF THE PROPERTIES
C   OF HELIUM AT VARIOUS PRESSURES (1-10 ATM) AND TEMPERATURES
C   (4.0-300.0 DEG K).
C   THE INPUT J SPECIFIES THE PROPERTY DESIRED.
C   1 = VISCOSITY (GRAMS/CM-SEC)
C   2 = DENSITY (GRAMS/CC)
C   3 = ENTHALPY (JOULES/GRAM)
C   4 = PRANDTL NUMBER
C   5 = HEAT CAPACITY (JOULES/GRAM-K)
C   6 = THERMAL CONDUCTIVITY OF HELIUM (WATT/CM-K)
C   7 = THERMAL CONDUCTIVITY OF COPPER (WATT/CM-K)
C   CALCULATION OF PROPERTIES IS DONE BY LINEAR INTERPOLATION
C   BETWEEN SPECIFIED DATA POINTS. THE KEY TO THE INDEXING
C   OF THESE DATA INPUT ARE BELOW.
C

C
C   THIS SECTION CONTAINS THE DATA POINTS, INTERPOLATED
C   SLOPES, AND INTERCEPTS FOR THE PROPERTIES AT DIFFERENT
C   PRESSURES.
C

C   THE KEY TO THE INDEXING OF POINTS IS AS FOLLOWS:

C   T(X,Y,Z)=TEMPERATURE AT WHICH DATA IS EVALUATED
C   SLOPE(X,Y,Z) = SLOPE OF THE LINE BETWEEN TEMPERATURES
C   BCEPT(X,Y,Z) = INTERCEPT OF THE LINE
C   P(X,Z)=PRESSURE AT WHICH DATA IS EVALUATED
C   X=INDEX NUMBER FOR PRESSURE DATA POINTS
C   Y=INDEX NUMBER FOR TEMPERATURE DATA POINTS
C   Z=PROPERTY NUMBER
C   ALL INDEXES ARE INDEXED FROM 0.

C
C   FOR EXAMPLE, T(2,3,4) IS THE TEMPERATURE DATA POINT
C   AT PRESSURE #2, THE FOURTH DATA POINT IN THE SERIES,
C   AND EVALUATED FOR PROPERTY #4. THE CORRESPONDING
C   PRESSURE,P(2,4) IS THE THIRD PRESSURE IN THE SERIES,
C   AND EVALUATED FOR PROPERTY #4. ALL SLOPES AND INTERCEPTS
C   ARE INDEXED BY THE LOWER TEMPERATURE POINT ON THE LINE.
C   IN OTHER WORDS, SLOPE(2,2,2) AND BCEPT(2,2,2) ARE
C   USED TO CALCULATE PROPERTIES BETWEEN T(2,2,2) AND
C   T(2,3,2).

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00440 DIMENSION T(0:10,0:10,10),SLOPE(0:10,0:10,10),P(0:10,10)
00450 DIMENSION BCEPT(0:10,0:10,10)
00460 DATA SLOPE(2,0,1),SLOPE(2,1,1)/-4.4E-6,1.05E-6/
00470 DATA T(0,0,1),T(0,1,1),T(0,2,1),T(0,3,1)/4.0,5.0,30.0,300.0/
00480 DATA SLOPE(2,2,1)/0.561E-6/
00490 DATA BCEPT(2,0,1),BCEPT(2,1,1)/59.5E-6,15.9E-6/
00500 DATA BCEPT(2,2,1)/30.6E-6/
00510 DATA T(0,0,2),T(0,1,2),T(0,2,2),T(0,3,2)/4.,4.5,5.,5.2/
00520 DATA T(0,4,2),T(0,5,2),T(0,6,2),T(1,0,2)/7.,50.,300.,4./
00530 DATA T(1,1,2),T(1,2,2),T(1,3,2),T(1,4,2)/5.2,5.5,10.,50./
00540 DATA T(1,5,2)/300./
00550 DATA SLOPE(0,0,2),SLOPE(0,1,2)/-.2312,-.512E-2/
00560 DATA SLOPE(0,2,2),SLOPE(0,3,2)/-.36E-2,-.205E-2/
00570 DATA SLOPE(0,4,2),SLOPE(0,5,2)/-.1525E-3,-3.2436E-6/
00580 DATA SLOPE(1,0,2),SLOPE(1,1,2)/-3.13E-2,-1.006E-1/
00590 DATA SLOPE(1,2,2),SLOPE(1,3,2)/-6.990E-3,-2.679E-4/
00600 DATA SLOPE(1,4,2)/-0.076E-6/
00610 DATA BCEPT(0,0,2)/1.0549/
00620 DATA BCEPT(0,1,2),BCEPT(0,2,2)/.03754,.02994/
00630 DATA BCEPT(0,3,2),BCEPT(0,4,2)/.02100,0.597E-3/
00640 DATA BCEPT(0,5,2),BCEPT(1,0,2)/1.136E-3,.2617/
00650 DATA BCEPT(1,1,2),BCEPT(1,2,2)/1.030,.0031/
00660 DATA BCEPT(1,3,2),BCEPT(1,4,2)/1.502E-2,2.029E-3/
00670 DATA T(0,0,3),T(0,1,3),T(0,2,3),T(0,3,3)/4.,4.5,7.,10./
00680 DATA T(0,4,3),T(0,5,3),T(1,0,3),T(1,1,3)/15.,30.,4.,5./
00690 DATA T(1,2,3),T(1,3,3),T(1,4,3),T(1,5,3)/5.5,10.,20.,30./
00700 DATA T(2,0,3),T(2,1,3),T(2,2,3),T(2,3,3)/4.,5.,7.,15./
00710 DATA T(2,4,3),T(2,5,3)/20.,30./
00720 DATA SLOPE(0,0,3),SLOPE(0,1,3)/47.7,6.32/
00730 DATA SLOPE(0,2,3),SLOPE(0,3,3)/5.5,5.3/
00740 DATA SLOPE(0,4,3),SLOPE(1,0,3)/5.2,5.21/
00750 DATA SLOPE(1,1,3),SLOPE(1,2,3)/20.5,7.40/
00760 DATA SLOPE(1,3,3),SLOPE(1,4,3)/5.474,5.20/
00770 DATA SLOPE(2,0,3),SLOPE(2,1,3)/3.93,9.56/
00775 DATA SLOPE(2,2,3),SLOPE(2,3,3)/6.7075,5.572/
00780 DATA SLOPE(2,4,3)/5.30/
00790 DATA BCEPT(0,0,3),BCEPT(0,1,3)/-102.,4.1/
00800 DATA BCEPT(0,2,3),BCEPT(0,3,3)/9.663,11.57/
00810 DATA BCEPT(0,4,3),BCEPT(1,0,3)/13.02,-11.50/
00820 DATA BCEPT(1,1,3),BCEPT(1,2,3)/-120.,-12.4/
00830 DATA BCEPT(1,3,3),BCEPT(1,4,3)/7.66,11.5/
00840 DATA BCEPT(2,0,3),BCEPT(2,1,3)/-5.33,-33.5/
00850 DATA BCEPT(2,2,3),BCEPT(2,3,3)/-14.0725,4.16/
00860 DATA BCEPT(2,4,3)/0.0/
00870 DATA T(2,0,2),T(2,1,2),T(2,2,2),T(2,3,2)/4.,5.,6.5,7./
00880 DATA T(2,4,2),T(2,5,2),T(2,6,2),T(2,7,2)/11.,15.,20.,34./
00890 DATA T(2,8,2),T(2,9,2)/40.0,300.0/
00900 DATA SLOPE(2,0,2),SLOPE(2,1,2)/-1.45E-2,-3.274E-2/
00910 DATA SLOPE(2,2,2),SLOPE(2,3,2)/-3.044E-2,-0.902E-3/
00920 DATA SLOPE(2,4,2),SLOPE(2,5,2)/-.199E-2,-.922E-3/
00930 DATA SLOPE(2,6,2),SLOPE(2,7,2)/-.3695E-3,-.17033E-3/
00940 DATA BCEPT(2,0,2),BCEPT(2,1,2)/.2016,.2920/
00950 DATA BCEPT(2,2,2),BCEPT(2,3,2)/.32905,.12365/
00960 DATA BCEPT(2,4,2),BCEPT(2,5,2)/.04673,.03071/
00970 DATA BCEPT(2,6,2),BCEPT(2,7,2)/.01966,.01316/
00980 DATA BCEPT(2,8,2)/.603E-2/
00990 DATA SLOPE(2,8,2)/-.2E-4/
09000 DATA T(0,0,4),T(0,1,4),T(0,2,4),T(0,3,4)/4.,5.,6.,10./

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09010 DATA T(0.4.4),T(0.5.4)/50.,300./
09020 DATA SLOPE(0.0.4),SLOPE(0.1.4)/.16,-.09/
09030 DATA SLOPE(0.2.4),SLOPE(0.3.4)/-.015,1.75E-4/
09040 DATA SLOPE(0.4.4)/-1.52E-4/
09050 DATA T(1.0.4),T(1.1.4),T(1.2.4),T(1.3.4)/4.,6.,10.,50./
09060 DATA T(1.4.4)/300.0/
09070 DATA SLOPE(1.0.4),SLOPE(1.1.4)/.295,-.115/
09080 DATA SLOPE(1.2.4),SLOPE(1.3.4)/-.125E-2,-.16E-3/
09090 DATA BCEPT(1.0.4),BCEPT(1.1.4)/.5,1.91/
09100 DATA BCEPT(1.2.4),BCEPT(1.3.4)/.77,.718/
09110 DATA T(2.0.4),T(2.1.4),T(2.2.4),T(2.3.4)/4.,5.,6.,10./
09120 DATA T(2.4.4),T(2.5.4)/20.0,300./
09130 DATA SLOPE(2.0.4),SLOPE(2.1.4)/.165,.471/
09140 DATA SLOPE(2.2.4),SLOPE(2.3.4)/-.09025,-.0136/
09150 DATA SLOPE(2.4.4)/-.225E-3/
09160 DATA BCEPT(2.0.4),BCEPT(2.1.4)/-.066,-1.596/
09170 DATA BCEPT(2.2.4),BCEPT(2.3.4)/1.7715,1.005/
09180 DATA BCEPT(2.4.4)/.7375/
09190 DATA P(0.4),P(1.4),P(2.4)/1.0,2.5,5.0/
09200 DATA P(0.1),P(1.1),P(2.1)/1.0,2.5,5.0/
09210 DATA P(0.2),P(1.2),P(2.2)/1.0,2.5,5.0/
09220 DATA P(0.3),P(1.3),P(2.3)/1.0,2.5,5.0/
09230 DATA SLOPE(0.0.1),SLOPE(0.1.1)/-19.5E-6,1.29E-6/
09240 DATA SLOPE(0.2.1)/0.565E-6/
09250 DATA BCEPT(0.0.1),BCEPT(0.1.1)/111.4E-6,7.42E-6/
09260 DATA BCEPT(0.2.1)/29.3E-6/
09270 DATA T(1.0.1),T(1.1.1),T(1.2.1),T(1.3.1)/4.,6.,30.,300./
09280 DATA SLOPE(1.0.1),SLOPE(1.1.1)/-9.2E-6,1.17E-6/
09290 DATA SLOPE(1.2.1)/0.56E-6/
09300 DATA BCEPT(1.0.1),BCEPT(1.1.1)/73.7E-6,11.40E-6/
09310 DATA BCEPT(1.2.1)/30.0E-6/
09320 DATA T(0.0.5),T(0.1.5),T(0.2.5),T(0.3.5)/4.,4.5,6.5,32./
09330 DATA T(0.4.5)/300.0/
09340 DATA SLOPE(0.0.5),SLOPE(0.1.5)/7.856,-1.007/
09350 DATA SLOPE(0.2.5),SLOPE(0.3.5)/-.0241,-.7836E-4/
09360 DATA BCEPT(0.0.5),BCEPT(0.1.5)/-27.35,12.0935/
09370 DATA BCEPT(0.2.5),BCEPT(0.3.5)/5.985,5.2165/
09380 DATA T(1.0.5),T(1.1.5),T(1.2.5),T(1.3.5)/4.,5.,5.4,6./
09390 DATA T(1.4.5),T(1.5.5),T(1.6.5)/8.,32.,300./
09400 DATA SLOPE(1.0.5),SLOPE(1.1.5)/5.169,91.5125/
09410 DATA SLOPE(1.2.5),SLOPE(1.3.5)/-22.08,-1.0135/
09420 DATA SLOPE(1.4.5),SLOPE(1.5.5)/-.04571,-1.978E-4/
09430 DATA BCEPT(1.0.5),BCEPT(1.1.5)/-17.15,-440.07/
09440 DATA BCEPT(1.2.5),BCEPT(1.3.5)/164.54,20.05/
09450 DATA BCEPT(1.4.5),BCEPT(1.5.5)/6.71,5.25/
09460 DATA T(2.0.5),T(2.1.5),T(2.2.5),T(2.3.5)/4.,5.,6.,6.5/
09470 DATA T(2.4.5),T(2.5.5),T(2.6.5),T(2.7.5)/7.,8.,32.,50./
09480 DATA T(2.8.5)/300./
09490 DATA SLOPE(2.0.5),SLOPE(2.1.5)/1.777,4.421/
09500 DATA SLOPE(2.2.5),SLOPE(2.3.5)/0.102,-3.28/
09510 DATA SLOPE(2.4.5),SLOPE(2.5.5)/-3.232,-.1329/
09520 DATA SLOPE(2.6.5),SLOPE(2.7.5)/-.361E-2,-.164E-3/
09530 DATA BCEPT(2.0.5),BCEPT(2.1.5)/-3.997,-17.217/
09540 DATA BCEPT(2.2.5),BCEPT(2.3.5)/-39.303,34.68/
09550 DATA BCEPT(2.4.5),BCEPT(2.5.5)/34.344,9.551/
09560 DATA BCEPT(2.6.5),BCEPT(2.7.5)/5.414,5.2422/
09570 DATA P(0.5),P(1.5),P(2.5)/1.0,2.5,5.0/
09580 DATA T(0.0.6),T(0.1.6),T(0.2.6),T(0.3.6)/4.,4.5,12.,34./
09590 DATA T(0.4.6)/300./
09600 DATA SLOPE(0.0.6),SLOPE(0.1.6)/1.0E-4,1.2E-5/

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09610 DATA SLOPE(0.2.6),SLOPE(0.3.6)/7.9182E-6,4.444E-6/
09620 DATA BCEPT(0.0.6),BCEPT(0.1.6)/9.16E-4,5.2E-5/
09630 DATA BCEPT(0.2.6),BCEPT(0.3.6)/1.01E-4,2.1692E-4/
09640 DATA T(1.0.6),T(1.1.6),T(1.2.6),T(1.3.6)/4.,4.5.6.,34./
09650 DATA T(1.4.6)/300.0/
09660 DATA SLOPE(1.0.6),SLOPE(1.1.6)/.6E-5,-.42E-4/
09670 DATA SLOPE(1.2.6),SLOPE(1.3.6)/.0E-5,.44E-5/
09680 DATA BCEPT(1.0.6),BCEPT(1.1.6)/1.03E-4,3.99E-4/
09690 DATA BCEPT(1.2.6),BCEPT(1.3.6)/.1E-3,.22E-3/
09700 DATA T(2.0.6),T(2.1.6),T(2.2.6),T(2.3.6)/4.,4.5.6.,7./
09710 DATA T(2.4.6),T(2.5.6),T(2.6.6)/8.,34.,300./
09720 DATA SLOPE(2.0.6),SLOPE(2.1.6)/.16E-4,-.2E-4/
09730 DATA SLOPE(2.2.6),SLOPE(2.3.6)/-.27E-4,-.1E-4/
09740 DATA SLOPE(2.4.6),SLOPE(2.5.6)/.731E-5,.441E-5/
09750 DATA BCEPT(2.0.6),BCEPT(2.1.6)/.1553E-4,2.36E-4/
09760 DATA BCEPT(2.2.6),BCEPT(2.3.6)/3.06E-4,2.67E-4/
09770 DATA BCEPT(2.4.6),BCEPT(2.5.6)/1.2054E-4,2.27E-4/
09780 DATA P(0.6),P(1.6),P(2.6)/1.0,2.5,5.0/
09790 DATA T(2.0.1),T(2.1.1),T(2.2.1),T(2.3.1)/4.,8.,30.,300./
09800 DATA BCEPT(0.0.4),BCEPT(0.1.4)/0.052,1.382/
09810 DATA BCEPT(0.2.4),BCEPT(0.3.4)/.055,.69025/
09820 DATA BCEPT(0.4.4)/.7146/
09830 DATA T(3.0.2),T(3.1.2),T(3.2.2),T(3.3.2)/4.,6.,10.,15./
09840 DATA T(3.4.2),T(3.5.2),T(3.6.2)/30.,50.,300./
09850 DATA SLOPE(3.0.2),SLOPE(3.1.2)/-1.305E-2,-1.0675E-2/
09860 DATA SLOPE(3.2.2),SLOPE(3.3.2)/-4.3E-3,-9.707E-4/
09870 DATA SLOPE(3.4.2),SLOPE(3.5.2)/-2.577E-4,-2.5492E-5/
09880 DATA BCEPT(3.0.2),BCEPT(3.1.2)/.202,.23575/
09890 DATA BCEPT(3.2.2),BCEPT(3.3.2)/.092,.04218/
09900 DATA BCEPT(3.4.2),BCEPT(3.5.2)/.02055,0.9436E-3/
09910 DATA P(3.2)/0.0/
09920 DATA P(3.3)/0.0/
09930 DATA T(3.0.3),T(3.1.3),T(3.2.3),T(3.3.3)/4.,6.,10.,16./
09940 DATA T(3.4.3),T(3.5.3)/20.,30./
09950 DATA SLOPE(3.0.3),SLOPE(3.1.3)/4.005,0.2025/
09960 DATA SLOPE(3.2.3),SLOPE(3.3.3)/6.343,5.765/
09970 DATA SLOPE(3.4.3)/5.4/
09980 DATA BCEPT(3.0.3),BCEPT(3.1.3)/-4.44,-29.145/
09990 DATA BCEPT(3.2.3),BCEPT(3.3.3)/-10.553,-1.3/
10000 DATA BCEPT(3.4.3)/6.0/
10010 DATA P(3.5),T(3.0.5),T(3.1.5),T(3.2.5)/0.,4.,5.,8./
10020 DATA T(3.3.5),T(3.4.5),T(3.5.5),T(3.6.5)/10.,14.,20.,30./
10030 DATA T(3.7.5)/300./
10040 DATA SLOPE(3.0.5),SLOPE(3.1.5)/1.196,1.763/
10050 DATA SLOPE(3.2.5),SLOPE(3.3.5)/-.7675,-.4115/
10060 DATA SLOPE(3.4.5),SLOPE(3.5.5)/-.00403,-.0252/
10070 DATA SLOPE(3.6.5),BCEPT(3.0.5)/-.7074E-3,-1.942/
10080 DATA BCEPT(3.1.5),BCEPT(3.2.5)/-4.7753,15.466/
10090 DATA BCEPT(3.3.5),BCEPT(3.4.5)/11.906,7.333/
10100 DATA BCEPT(3.5.5),BCEPT(3.6.5)/6.14,5.4052/
10110 DATA T(3.0.1),T(3.1.1),T(3.2.1),T(3.3.1)/4.,9.,15.,30./
10120 DATA T(3.4.1),T(3.5.1)/100.,300./
10130 DATA SLOPE(3.0.1),SLOPE(3.1.1)/-0.05E-6,0.33E-7/
10140 DATA SLOPE(3.2.1),SLOPE(3.3.1)/9.07E-7,7.2E-7/
10150 DATA SLOPE(3.4.1),BCEPT(3.0.1)/5.065E-7,0.25E-5/
10160 DATA BCEPT(3.1.1),BCEPT(3.2.1)/2.1E-5,1.07E-5/
10170 DATA BCEPT(3.3.1),BCEPT(3.4.1)/2.67E-5,4.005E-5/
10180 DATA T(3.0.4),T(3.1.4),T(3.2.4),T(3.3.4)/4.,5.5.6.,8./
10190 DATA T(3.4.4),T(3.5.4),T(3.6.4)/10.,00.,300./
10200 DATA SLOPE(3.0.4),SLOPE(3.1.4)/.0013,.144/

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10210 DATA SLOPE(3.2,4),SLOPE(3.3,4)/.203,-.416E-1/
10220 DATA SLOPE(3.4,4),SLOPE(3.5,4)/-.10645E-2,-.1364E-3/
10230 DATA BCEPT(3.0,4),BCEPT(3.1,4)/.2547,-.09/
10240 DATA BCEPT(3.2,4),BCEPT(3.3,4)/-.444,1.5128/
10250 DATA BCEPT(3.4,4),BCEPT(3.5,4)/.7832,.78891/
10260 DATA T(3.0,6),T(3.1,6),T(3.2,6),T(3.3,6)/4.,6.,9.,25./
10270 DATA T(3.4,6),T(3.5,6)/50.,300./
10280 DATA SLOPE(3.0,6),SLOPE(3.1,6)/1.1E-5,-1.03E-5/
10290 DATA SLOPE(3.2,6),SLOPE(3.3,6)/6.44E-6,6.2E-6/
10300 DATA SLOPE(3.4,6),BCEPT(3.0,6)/4.20E-6,1.07E-4/
10310 DATA BCEPT(3.1,6),BCEPT(3.2,6)/3.15E-4,1.64E-4/
10320 DATA BCEPT(3.3,6),BCEPT(3.4,6)/1.7E-4,1.34E-3/
10330 DATA P(3.1),P(3.4),P(3.6)/8.,8.,8./
10340 DATA T(0.0,7),T(0.1,7),T(0.2,7),T(0.3,7)/4.,26.,60.,300./
10350 DATA SLOPE(0.0,7),SLOPE(0.1,7)/1.1,.02/
10360 DATA SLOPE(0.2,7)/.40/
10370 DATA BCEPT(0.0,7),BCEPT(0.1,7)/.01533,.038387/
10380 DATA BCEPT(0.2,7)/.15531/
10390
10400 C      THIS SECTION IS THE LINEAR INTERPOLATION AND
10410 CC     PROPERTIES EVALUATION.  N IS THE INDEX COUNTER FOR
10420 C      THE PRESSURE DATA POINTS.  I IS THE INDEX COUNTER FOR
10430 C      THE TEMPERATURE DATA POINTS.  J IS THE PROPERTY NUMBER.
10440 C
10450 I=0
10460 N=0
10470 C      CHECK TO SEE IF COPPER THERMAL COND. IS DESIRED.
10480 IF (J.EQ.7) GO TO 333
10490
10500 C      DETERMINE BETWEEN WHICH TWO PPRESSURE DATA POINTS IS
10510 C      THE DESIRED PRESSURE.
10520
10530 9      IF (P(N,J)-PRESS) 10,20,30
10540 10     N=N+1
10550     IF (N.GT.3) GO TO 25
10560     GO TO 9
10570 20     GO TO 100
10580 25     N=3
10590     GO TO 100
10600 C      FIND THE SLOPE AND INTERCEPT DATA FOR THE TEMPERATURE
10610 C      AT THE LOWER PRESSURE.
10620 30     IF (T(N-1,I,J)-TEMP) 40,60,60
10630 40     I=I+1
10640     GO TO 30
10650 C      CALCULATE THE PROPERTY VALUE AT THE LOWER PRESSURE AND
10660 C      DESIRED TEMPERATURE.
10670 60     X1=SLOPE(N-1,I-1,J)*TEMP+BCEPT(N-1,I-1,J)
10680     I=0
10690 C      FIND THE SLOPE AND INTERCEPT DATA FOR THE TEMPERATURE
10700 C      AT THE HIGHER PRESSURE.
10710 65     IF (T(N,I,J)-TEMP) 70,90,90
10720 70     I=I+1
10730     GO TO 65
10740 C      FIND THE SLOPE AND INTERCEPT DATA FOR THE TEMPERATURE
10750 C      AT THE HIGHER PRESSURE.
10760 90     X2=SLOPE(N,I-1,J)*TEMP+BCEPT(N,I-1,J)
10770     GO TO 140
10780 100    I=0
10790 C      IF PRESSURE IS EXACTLY EQUAL TO ONE OF THE PRESSURE DATA
10800 C      VALUES, FIND THE SLOPE AND INTERCEPT DATA FOR THAT PRESSURE.

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10010 105 IF (T(N,I,J)-TEMP) 110,130,130
10020 110 I=I+1
10030 GO TO 105
10031 DATA T(0.6,3),T(1.6,3),T(2.6,3),T(3.6,3)/300.,300.,300.,300./
10032 DATA SLOPE(0.5,3),SLOPE(1.5,3)/5.196,5.197/
10033 DATA SLOPE(2.5,3),SLOPE(3.5,3)/5.197,5.200/
10034 DATA BCEPT(0.5,3),BCEPT(1.5,3)/14.3,14.8/
10035 DATA BCEPT(2.5,3),BCEPT(3.5,3)/14.8,12.6/
10040 C CALCULATE THE VALUE OF THE PROPERTY AT THE DESIRED TEMP.
10050 C DESIRED TEMPERATURE.
10060 130 ZPROP=SLOPE(N,I-1,J)*TEMP+BCEPT(N,I-1,J)
10070 GO TO 150
10080 C INTERPOLATE BETWEEN THE TWO PRESSURES TO DETERMINE
10090 C THE PROPERTY VALUE.
10090 140 SLOP=(X1-X2)/(P(N-1,J)-P(N,J))
10091 B= X1-SLOP*P(N-1,J)
10092 ZPROP=SLOP*PRESS+B
10093 GO TO 150
10094
10095 C THIS SECTION CALCULATES THE THERMAL CONDUCTIVITY OF COPPER.
10096 333 IF (T(0,I,J)-TEMP) 334,335,335
10097 334 CONTINUE
10098 I=I+1
10099 GO TO 333
10099 335 ZPROP=BCEPT(0,I-1,J)*TEMP+SLOPE(0,I-1,J)
10100 GO TO 150
10110 150 CONTINUE
10120 RETURN
10130 END

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SCHOOL OF CHEMICAL ENGINEERING PRACTICE
AT
OAK RIDGE NATIONAL LABORATORY

FLOW CHART FOR PROPERTIES
OF HELIUM PROGRAM

DATE 10-26-76	DRAWN BY BYT	FILE NO. CFPS-X-242	FIG. 11c
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10.2 Nomenclature

A	area of heat transfer, cm^2
C	constant for boiling heat transfer, Eq. (1)
C_p	heat capacity, $\text{joules/gm-}^\circ\text{K}$
D	diameter of pipe in exchanger, cm
F	friction factor
h	heat transfer coefficient, $\text{W/cm}^2\text{-}^\circ\text{K}$
H	specific enthalpy, joules/gm
k	thermal conductivity, $\text{W/cm-}^\circ\text{K}$
L	length of tube segment, cm
L_{CC}	countercurrent exchanger length, m
L_{He}	helium bath exchanger length, m
L_{N_2}	nitrogen bath exchanger length, m
$\dot{M}$	mass flow rate, gm/sec
n	exponent in boiling heat transfer, Eq. (1)
Nu	Nusselt number, hD/k
P	pressure, atm
Pr	Prandtl number, $k/\mu C_p$
ΔP	pressure drop, atm
Q	rate of heat transfer, joule/sec
Re	Reynolds number, $\rho Dv/\mu$
R_h	hydraulic radius, cm
r	radius, cm
T	temperature, $^\circ\text{K}$
t	tube wall thickness, cm

ΔT	temperature difference, °K
U	overall heat transfer coefficient, $W/cm^2 \cdot ^\circ K$
v	fluid velocity, cm/sec
μ	viscosity, gm/cm-sec
ρ	density, gm/cm ³

Subscripts

in	inside wall of 0.635 cm (0.25 in.) copper tube
io	inside wall of the outer tube in the countercurrent exchanger
out	outer wall of 0.635 cm (0.25 in.) copper tube
l_{He}	liquid helium bath
l_{N_2}	liquid nitrogen bath
b	bulk properties of helium
bc	bulk properties of helium from magnet test section
c	coiled tube
M	magnet
s	shell bulk properties
t	inner tube bulk properties
o	inlet conditions
l	exit conditions
w	at a tube wall

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