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ORNL-TM-2815

COMPUTER PROGRAMS FOR MSBR HEAT EXCHANGERS

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NUCLEAR DIVISION

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OAK RIDGE, TENNESSEE 37830

June 24, 1971

To: Recipients of Subject Report

Report No.: ORNL-TM-2815 Classification: Unclassified

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Subject: Computer Programs For MSBR Heat Exchangers

Request compliance with indicated action:

Please affix the attached corrected pages 6, 7, 58, 62, 63, 86, 87, 88, 89, 117, 124, 125 to pages with same numbers in your copy(ies) of the subject report. They are prepared on gummed stock for your convenience. Also prepared on gummed stock is a correction for the bottom two lines on page 9 of the report.

Please correct your copies promptly to avoid further errors. The corrected design data for the primary heat exchanger agree with the data shown in Report No. ORNL-4541.

Laboratory Records Department
Technical Information Division

Table 2.1. Design Data for MSBR Primary Heat Exchanger

Type	Shell-and-tube one-pass vertical exchanger with disk and doughnut baffles
Number required	Four
Rate of heat transfer per unit,	
MW	556.5
Btu/hr	1.9×10^9
Tube-side conditions	
Hot fluid	Fuel salt
Entrance temperature, °F	1300
Exit temperature, °F	1050
Entrance pressure, psi	180
Pressure drop across exchanger, psi	130
Mass flow rate, lb/hr	23.4×10^6
Shell-side conditions	
Cold fluid	Coolant salt
Entrance temperature, °F	850
Exit temperature, °F	1150
Exit pressure, psi	34
Pressure drop across exchanger, psi	115.7
Mass flow rate, lb/hr	17.8×10^6
Tube	
Material	Hastelloy N
Number required	5803
Pitch, in.	0.75
Outside diameter, in.	0.375
Wall thickness, in.	0.035
Length, ft	24.4
Tube sheet	
Material	Hastelloy N
Thickness, in.	4.75
Sheet-to-sheet distance, ft	23.2
Total heat transfer area, ft^2	13,916
Basis for area calculation	Outside of tubes
Volume of fuel salt in tubes, ft^3	71.9
Shell	
Material	Hastelloy N
Thickness, in.	0.5
Inside diameter, in.	67.6
Central tube diameter, in.	20.0
Baffle	
Type	Disk and doughnut
Number	21
Spacing, in.	11.23

Table 2.1 (continued)

Disk outside diameter, in.	54.20
Doughnut inside diameter, in.	45.3
Overall heat transfer coefficient, U, Btu/hr·ft^2·°F	784.8
Tube	
Maximum primary (P) stresses	
Calculated, psi	683
Allowable, psi	4232
Maximum primary and secondary (P + Q) stresses	
Calculated, psi	12,484
Allowable, psi	12,696
Maximum peak (P + Q + F) stresses	
Calculated, psi	13,563
Allowable, psi	25,000

wave configuration. The tubes are held in place by wire lacing in this upper portion of the tube bundle. Since baffling is not employed in this region, the bent-tube portion of the bundle experiences essentially parallel flow and a relatively lower heat transfer performance.

Below the bent-tube region of the bundle, evenly spaced doughnut-shaped baffles are used to hold the tubes in place and to produce cross flow. The baffles spacings and cross-flow velocities are designed to minimize the possibility of flow-induced vibration. The tubes in this baffled region of the heat exchanger have a helical indentation knurled into their surface to enhance the film heat transfer coefficients and thereby reduce the fuel salt inventory in the exchanger. No enhancement of this nature was used in the upper bent-tube region because of present uncertainty about the reliability of tubes that are both bent and indented.

Bottom of page 9:

For completely turbulent flow with Reynolds numbers greater than 12,000,

$$\frac{h_i d_i}{k_i} = 0.0217(N_{Re})^{0.8}(N_{Pr})^{1/3}\left(\frac{\mu_b}{\mu_i}\right)^{0.14}(EF_i) \qquad (2.3)$$

```
 1047 FORMAT(31H0BERGLIN MODIFICATION FACTOR = ,F5.2)                     MSBR 500
 1048 FORMAT(1H0,2X,1HI,7X,3HTCI,9X,3HTCO,9X,3HCWT,9X, 3HTFI,9X,3HTFO,    MSBR 510
     19X,3HFWT,8X,4HTWDT//11X,1HF,11X,1HF,11X,1HF,11X,                    MSBR 511
     2      1HF,11X,1HF,11X,1HF,11X,1HF//(1X,I3,7E12.4))                  MSBR 512
 1049 FORMAT(1H0,2X,1HI,9X,2HV1, 9X,2HV2 ,9X,2HV3 ,9X,3HVW1 ,9X,3HVW3 ,   MSBR 520
     1 8X,4HPDSO,8X,4HPDTO//32X,6HFT/SEC,33X,7HLB/SQFT//(1X,I3,7F12.4))  MSBR 521
 1050 FORMAT(1H0,2X,1HI,5X,5HRENTO,7X,5HPRNTO,7X,6HRENSO1,6X,6HRENSO2,    MSBR 530
     16X,6HRENSO3,7X,3HHTO,8X,4HAHSO,9X,3HUOA,8X,4HHEAT//77X,            MSBR 531
     2  13HBTU/HR/SQFT/F,13X,6HBTU/HR//(1X,I3,9E12.4))                   MSBR 532
 1051 FORMAT(27H0TUBE WALL AVERAGE TEMP. =  ,F10.2)                       MSBR 540
 1052 FORMAT(28H0SHELL SIDE AVERAGE TEMP. =  , F10.2)                     MSBR 550
 1053 FORMAT(1H0,34HP STRESS AT TUBE OD AND TUBE ID = ,     2F10.2,1X,    MSBR 560
     1 9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,3H  ))                   MSBR 561
 1054 FORMAT(1H0,36HP+Q STRESS AT TUBE OD AND TUBE ID = ,                 MSBR 570
     1           2F10.2,1X,9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,     MSBR 571
     2 3H  ))                                                            MSBR 572
 1055 FORMAT(1H0,38HP+Q+F STRESS AT TUBE OD AND TUBE ID = ,               MSBR 580
     1           2F10.2,1X,9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,     MSBR 581
     2 3H  ))                                                            MSBR 582
C                                                                        MSBR 650
C     READ IN AND PRINT OUT INPUT DATA                                   MSBR 660
      KEY7= 1                                                            MSBR 610
      VM1(1)=0.                                                          MSBR 620
      VM2(1)=0.                                                          MSBR 630
      VM3(1)=0.                                                          MSBR 640
      VWO1(1)=0.                                                         MSBR 650
      VWO3(1)=0.                                                         MSBR 660
      RENSO1(1)=0.                                                       MSBR 670
      RENSO2(1)=0.                                                       MSBR 680
      RENSO3(1)=0.                                                       MSBR 690
      HSO1(1)=0.                                                         MSBR 700
      HSO2(1)=0.                                                         MSBR 710
      HSO3(1)=0.                                                         MSBR 720
C                                                                        MSBR 810
```

```
      IF(KEY1.EQ.0)BSOI=0.5*(BSL+BSH)                                   MSB 1850
      CURVES=0.069813*ARC*  EXPRAD+ 0.4*(RA8-RA5)+.25*BSOI              MSB 1860
      IT = 0                                                            MSB 1870
      KFINAL=0                                                          MSB 1880
    9 I=1                                                               MSB 1890
      HEFI = 1.                                                         MSBR 730
      HEFO = 1.                                                         MSBR 740
      TSUM=0.                                                           MSB 1900
      SSUM=0.                                                           MSB 1910
      THEATO = 0.0                                                      MSB 1920
      TPDTO = 0.0                                                       MSB 1930
      TPDSO = 0.0                                                       MSB 1940
      TFO(I)=FTC                                                        MSB 1950
      TCI(I)=CTC                                                        MSB 1960
      TIF=-5.0                                                          MSB 1970
      TIC=-5.0                                                          MSB 1980
      CDTF=0.                                                           MSB 1990
      FDTF=0.                                                           MSB 2000
      BSO = BSOI                                                        MSB 2010
      BRL1 = BSO/((RA8-(RA8-RA7)/2.)-(RA5+(RA6-RA5)/2.))                MSB 2020
      GBRL = 0.77*BRL1**(-.138)                                         MSB 2030
      AWO1 = BSO*LAWO1                                                  MSB 2040
      AWO3 = BSO*LAWO3                                                  MSB 2050
      AW1  = SQRT(AWO1*APO1)                                            MSB 2060
      AW2  = (AWO1+AWO3)/2.                                             MSB 2070
      AW3  = SQRT(AWO3*APO3)                                            MSB 2080
      GSO1 = QC/AW1                                                     MSB 2090
      GSO2 = QC/AW2                                                     MSB 2100
      GSO3 = QC/AW3                                                     MSB 2110
      BSO=CURVES                                                        MSB 2120
      EQVBSO= CURVES+ 13.*(DIA+DIAI)                                    MSB 2130
      KEY4=0                                                            MSB 2140
   10 KEY5=0                                                            MSB 2150
   11 ATC = TCI(I) + (TIC/2.0)                                          MSB 2160
      CFT = ATC +CDTF*HSFCT
      ATF = TFO(I)+TIF/2.                                               MSB 2180
      FFT=ATF-FDTF*HSFCT
      FI=I                                                              MSB 2200
      TUBLN(I) =(FI-1.)*BSOI+CURVES                                     MSB 2210
```

```
      CVIS=0.2121*EXP(4032./(460.+ATC))                                 MSB 2220
      CVISW=0.2121*EXP(4032./(460.+CFT))                                MSB 2230
      CDEN=141.37-0.02466*ATC                                           MSB 2240
      CCON=0.240                                                        MSB 2250
      CSPH=0.36                                                         MSB 2260
      FVIS=0.2637*EXP(7362./(460.+ATF))                                 MSB 2270
      FVISW=0.2637*EXP(7362./(460.+FFT))                                MSB 2280
      FDEN=234.97-0.02317*ATF                                           MSB 2290
      FCON=0.70                                                         MSB 2300
      FSPH=0.324                                                        MSB 2310
      VISK = (CVIS/CVISW)**0.14                                         MSB 2320
      FVISK=(FVIS/FVISW)**0.14                                          MSB 2330
      DCVIS = DIA/CVIS                                                  MSB 2340
      CCDEN = 1./CDEN                                                   MSB 2350
      QCCDEN = QC*CCDEN                                                 MSB 2360
C     CALCULATE REYNOLS AND PRANDTL NUMBER TUBE SIDE                    MSB 2550
      RENTO(I)=DIAI*GTO/FVIS                                            MSB 2380
      PRNTO(I)=FVIS*FSPH/FCON                                           MSB 2390
      IF(KENTB.EQ.1.AND.RENTO(I) .GT.1001. .AND.I.NE.1)                 MSB 2400
     1HEFI=1.+((RENTO(I)-1000.)/9000.)**0.5                             MSB 2401
      PDTO(I)=(.0028+.25*RENTO**(-.32))*EQVBSO*GTO**2*HEFI/             MSB 2410
     1        (DIAI*FDEN*417182400.)                                    MSB 2411
C     CALCULATE HEAT TRANSFER COEFF TUBE SIDE                           MSB 2640
      IF(RENTO(I).LT.12000.)GO TO 12
      HTO(I)=FCON/DIA*.0217*(RENTO(I)**.8)*(PRNTO(I)**.3333)*FVISK*HEFI MSB 2430
      GO TO 15                                                          MSB 2440
 12   IF(RENTO(I).LT.2100.) GO TO 14                                    MSB 2450
 13   HTO(I) = FCON/DIA*.089*(RENTO(I)**.67895-141.1372)*(PRNTO(I)
     1**.3333)*FVISK*HEFI*(1.+.3333*(DIAI/TUBLN(I))**.6666)
      GO TO 15                                                          MSB 2470
 14   HTO(I) = FCON/DIA*(4.36+(0.025*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)    MSB 2480
     1  )/(1.+0.0012*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)))                  MSB 2481
 15   IF(I.EQ.1)GO TO 16                                                MSB 2490
C     CALCULATE FLOW AREAS SHELL SIDE                                   MSB 2480
      VWO1(I) =  QCCDEN/AWO1                                            MSB 2510
      VWO3(I) =  QCCDEN/AWO3                                            MSB 2520
      VM1(I) = GSO1*CCDEN                                               MSB 2530
      VM2(I) = GSO2*CCDEN                                               MSB 2540
      VM3(I) = GSO3*CCDEN                                               MSB 2550
```

Computer Output for Reference MSBR Primary Heat Exchanger

```
TOTAL HEAT TRANSFERED =  1898217984.  (BTU/HR)  ( 99.9 PERCENT)

MASS FLOW RATE OF COOLANT =  17590736.  (LB/HR)

MASS FLOW RATE OF FUEL =  23454320.  (LB/HR)

SHELL-SIDE TOTAL PRESSURE DROP =     115.75  (LB/SQIN)  ( 99.7 PERCENT)

TUBE-SIDE TOTAL PRESSURE DROP =     129.32  (LB/SQIN)  ( 99.5 PERCENT)

NOMINAL SHELL RADIUS =  2.8162  (FT)

UNIFORM BAFFLE SPACING =  0.9386  (FT)

TUBE FLUID VOLUME CONTAINED IN TUBES =   71.92 (CUBIC FEET)

TOTAL HEAT TRANSFER AREA BASED ON TUBE O.D. =     13916.32  (SQFT)

TOTAL NUMBER OF TUBES =  5803.

TOTAL TUBE LENGTH =  24.43  (FT)

HEAT EXCH. APPROX. LENGTH =  23.22  (FEET)

STRAIGHT SECTION OF TUBE LENGTH =  20.26  (FT)

RADIUS OF THERMAL EXPANSION CURVES =   0.86  (FEET)

BERGLIN MODIFICATION FACTOR =  0.79

TUBE WALL AVERAGE TEMP. =    1116.54

SHELL SIDE AVERAGE TEMP. =    1013.66
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P STRESS AT TUBE OD AND TUBE ID =      683.42    646.47 (LB/SQIN)

SHOULD NOT EXCEED   4232.23   )

P+Q STRESS AT TUBE OD AND TUBE ID =   12484.39   8890.97 (LB/SQIN)

SHOULD NOT EXCEED  12696.70   )

P+Q+F STRESS AT TUBE OD AND TUBE ID =   13562.77  10981.55 (LB/SQIN)

SHOULD NOT EXCEED  25000.00   )

  I        TCI         TCO         CWT         TFI         TFO         FWT         TWDT

            F           F           F           F           F           F            F

  1  0.1150E 04  0.1122E 04  0.1240E 04  0.1276E 04  0.1300E 04  0.1256E 04  0.1549E 02
  2  0.1122E 04  0.1108E 04  0.1178E 04  0.1265E 04  0.1276E 04  0.1223E 04  0.4528E 02
  3  0.1108E 04  0.1094E 04  0.1165E 04  0.1254E 04  0.1265E 04  0.1210E 04  0.4516E 02
  4  0.1094E 04  0.1081E 04  0.1152E 04  0.1242E 04  0.1254E 04  0.1198E 04  0.4525E 02
  5  0.1081E 04  0.1067E 04  0.1139E 04  0.1231E 04  0.1242E 04  0.1185E 04  0.4533E 02
  6  0.1067E 04  0.1053E 04  0.1126E 04  0.1219E 04  0.1231E 04  0.1172E 04  0.4538E 02
  7  0.1053E 04  0.1039E 04  0.1113E 04  0.1208E 04  0.1219E 04  0.1159E 04  0.4540E 02
  8  0.1039E 04  0.1025E 04  0.1100E 04  0.1196E 04  0.1208E 04  0.1146E 04  0.4540E 02
  9  0.1025E 04  0.1012E 04  0.1087E 04  0.1185E 04  0.1196E 04  0.1133E 04  0.4538E 02
 10  0.1012E 04  0.9979E 03  0.1074E 04  0.1173E 04  0.1185E 04  0.1119E 04  0.4532E 02
 11  0.9979E 03  0.9842E 03  0.1061E 04  0.1162E 04  0.1173E 04  0.1106E 04  0.4524E 02
 12  0.9842E 03  0.9705E 03  0.1048E 04  0.1150E 04  0.1162E 04  0.1093E 04  0.4513E 02
 13  0.9705E 03  0.9569E 03  0.1035E 04  0.1139E 04  0.1150E 04  0.1080E 04  0.4499E 02
 14  0.9569E 03  0.9433E 03  0.1022E 04  0.1128E 04  0.1139E 04  0.1067E 04  0.4482E 02
 15  0.9433E 03  0.9297E 03  0.1009E 04  0.1116E 04  0.1128E 04  0.1053E 04  0.4462E 02
 16  0.9297E 03  0.9162E 03  0.9957E 03  0.1105E 04  0.1116E 04  0.1040E 04  0.4440E 02
 17  0.9162E 03  0.9029E 03  0.9827E 03  0.1094E 04  0.1105E 04  0.1027E 04  0.4414E 02
 18  0.9029E 03  0.8895E 03  0.9697E 03  0.1083E 04  0.1094E 04  0.1014E 04  0.4385E 02
 19  0.8895E 03  0.8763E 03  0.9568E 03  0.1072E 04  0.1083E 04  0.1000E 04  0.4353E 02
 20  0.8763E 03  0.8632E 03  0.9439E 03  0.1061E 04  0.1072E 04  0.9871E 03  0.4318E 02
 21  0.8632E 03  0.8503E 03  0.9311E 03  0.1050E 04  0.1061E 04  0.9739E 03  0.4280E 02
```

```
  I        V1        V2        V3        VW1       VW3       PDSO        PDTO

                               FT/SEC                          LB/SQFT

  1      0.0       0.0       0.0       0.0       0.0       847.4312   2869.1321
  2      6.1833    6.9424    6.7222    6.3719    7.6251    847.4312    861.8818
  3      6.1649    6.9218    6.7022    6.3530    7.6025    841.4097    853.9431
  4      6.1467    6.9014    6.6825    6.3342    7.5801    835.4158    846.0403
  5      6.1286    6.8810    6.6628    6.3155    7.5577    829.4214    838.1379
  6      6.1106    6.8608    6.6432    6.2970    7.5355    823.4299    830.2402
  7      6.0926    6.8406    6.6236    6.2785    7.5133    817.4436    822.3506
  8      6.0748    6.8206    6.6042    6.2601    7.4913    811.4666    814.4746
  9      6.0570    6.8006    6.5849    6.2418    7.4694    805.5010    806.6165
 10      6.0394    6.7808    6.5658    6.2236    7.4477    799.5500    798.7803
 11      6.0219    6.7612    6.5467    6.2055    7.4261    793.6187    790.9712
 12      6.0045    6.7416    6.5278    6.1876    7.4046    787.7100    783.1938
 13      5.9872    6.7223    6.5091    6.1699    7.3834    781.8259    775.4529
 14      5.9702    6.7031    6.4905    6.1522    7.3623    775.9714    767.7529
 15      5.9532    6.6841    6.4721    6.1348    7.3414    770.1499    760.0996
 16      5.9365    6.6653    6.4539    6.1175    7.3208    764.3652    752.4968
 17      5.9199    6.6467    6.4358    6.1004    7.3003    758.6204    744.9495
 18      5.9035    6.6283    6.4180    6.0836    7.2801    752.9199    737.4634
 19      5.8873    6.6101    6.4004    6.0669    7.2601    747.2676    730.0410
 20      5.8713    6.5921    6.3830    6.0504    7.2404    741.6660    722.6892
 21      5.8555    6.5744    6.3659    6.0341    7.2210    736.1208    715.4114
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```
 I     RENTO       PRNTC       RENSO1      RENSO2      RENSO3       HTO         AHSO        UOA         HEAT

                                                                          BTU/HR/SQFT/F            BTU/HR

 1  0.1138E 05  0.8232E 01  0.0         0.0         0.0         0.1732E 04  0.5314E 03  0.3653E 03  0.1793E 09
 2  0.1091E 05  0.8589E 01  0.2887E 05  0.3241E 05  0.3138E 05  0.3422E 04  0.2580E 04  0.1044E 04  0.8700E 08
 3  0.1061E 05  0.8835E 01  0.2822E 05  0.3169E 05  0.3068E 05  0.3318E 04  0.2532E 04  0.1026E 04  0.8678E 08
 4  0.1031E 05  0.9092E 01  0.2758E 05  0.3097E 05  0.2999E 05  0.3232E 04  0.2507E 04  0.1014E 04  0.8695E 08
 5  0.1001E 05  0.9360E 01  0.2695E 05  0.3026E 05  0.2930E 05  0.3147E 04  0.2481E 04  0.1001E 04  0.8710E 08
 6  0.9721E 04  0.9641E 01  0.2631E 05  0.2955E 05  0.2861E 05  0.3063E 04  0.2456E 04  0.9881E 03  0.8719E 08
 7  0.9434E 04  0.9934E 01  0.2568E 05  0.2884E 05  0.2792E 05  0.2979E 04  0.2430E 04  0.9751E 03  0.8724E 08
 8  0.9151E 04  0.1024E 02  0.2506E 05  0.2813E 05  0.2724E 05  0.2896E 04  0.2403E 04  0.9619E 03  0.8724E 08
 9  0.8874E 04  0.1056E 02  0.2443E 05  0.2743E 05  0.2656E 05  0.2814E 04  0.2377E 04  0.9485E 03  0.8719E 08
10  0.8601E 04  0.1090E 02  0.2382E 05  0.2674E 05  0.2589E 05  0.2732E 04  0.2351E 04  0.9349E 03  0.8708E 08
11  0.8333E 04  0.1125E 02  0.2320E 05  0.2605E 05  0.2523E 05  0.2651E 04  0.2324E 04  0.9211E 03  0.8692E 08
12  0.8071E 04  0.1161E 02  0.2260E 05  0.2537E 05  0.2456E 05  0.2571E 04  0.2298E 04  0.9071E 03  0.8672E 08
13  0.7814E 04  0.1199E 02  0.2199E 05  0.2469E 05  0.2391E 05  0.2492E 04  0.2271E 04  0.8929E 03  0.8645E 08
14  0.7562E 04  0.1239E 02  0.2140E 05  0.2403E 05  0.2326E 05  0.2413E 04  0.2245E 04  0.8786E 03  0.8612E 08
15  0.7316E 04  0.1281E 02  0.2081E 05  0.2337E 05  0.2263E 05  0.2335E 04  0.2218E 04  0.8640E 03  0.8574E 08
16  0.7075E 04  0.1325E 02  0.2023E 05  0.2272E 05  0.2199E 05  0.2258E 04  0.2192E 04  0.8493E 03  0.8531E 08
17  0.6840E 04  0.1370E 02  0.1966E 05  0.2207E 05  0.2137E 05  0.2183E 04  0.2165E 04  0.8345E 03  0.8481E 08
18  0.6611E 04  0.1417E 02  0.1910E 05  0.2144E 05  0.2076E 05  0.2108E 04  0.2139E 04  0.8194E 03  0.8426E 08
19  0.6389E 04  0.1467E 02  0.1854E 05  0.2082E 05  0.2016E 05  0.2034E 04  0.2112E 04  0.8042E 03  0.8364E 08
20  0.6172E 04  0.1518E 02  0.1800E 05  0.2021E 05  0.1956E 05  0.1961E 04  0.2086E 04  0.7888E 03  0.8297E 08
21  0.5961E 04  0.1572E 02  0.1746E 05  0.1961E 05  0.1898E 05  0.1889E 04  0.2059E 04  0.7733E 03  0.8224E 08
```

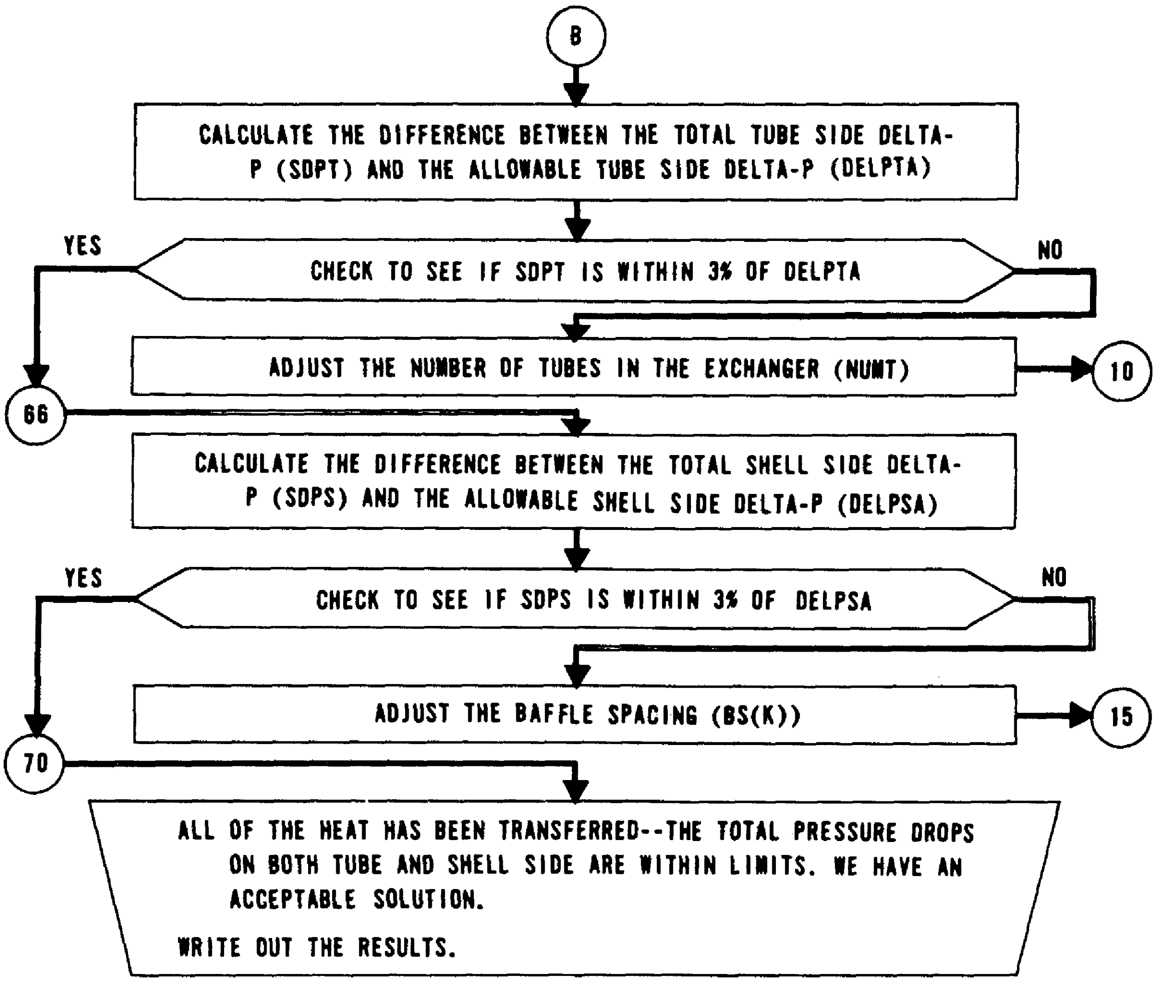

Fig. D.1. (continued)

```
      MS=1                                                              SUP 1020
      SX=0                                                              SUP 1030
      SBS=0                                                             SUP 1040
      TC(1)=TC2                                                         SUP 1050
      TH(1)=TH1                                                         SUP 1060
      RWK=DTO*LOGF(DTO/DTI)/2.0                                         SUP 1070
      PC(1)=PC2                                                         SUP 1080
      CALL SVH(2,PC2,TC2,DUM,HC(1))                                     SUP 1090
      BN=FLOATF(N)                                                      SUP 1100
      QX=QT/BN                                                          SUP 1110
      DECT=QX/(WH*CPH)                                                  SUP 1120
      DECH=QX/WC                                                        SUP 1130
      I=1                                                               SUP 1140
      K=1                                                               SUP 1150
   16 SB = SBK*BSL                                                      SUP 1160
      LOP7=0                                                            SUP 1170
      TCON=TH(I)-DTPB/2.0                                               SUP 1180
      IF(I.EQ.1) GO TO 161                                              SUP*1181
      VMUO=0.2122*EXPF(4032./(TW+460.))                                 SUP*1182
      VMUB=0.2122*EXPF(4032./(TCON+460.))                               SUP*1183
      FACT=(VMUO/VMUB)**0.14                                            SUP*1184
      GO TO 162                                                         SUP*1185
  161 FACT=1.0                                                          SUP*1186
  162 CONTINUE                                                          SUP*1187
      DENH=141.38E+00-2.466E-02*TCON                                    SUP 1190
      VISH=0.2122E+00*EXPF(4032.0E+00/(TCON+460.0E+00))                 SUP 1200
      DHOT(K)=DENH                                                      SUP 1210
      VHOT(K)=VISH                                                      SUP 1220
      CON1=(CPH*VISH/TCH)**0.667E+00                                    SUP 1230
      GM=WH/SB                                                          SUP 1240
      RECB=DTO*GM/VISH                                                  SUP 1250
      IF(RECB-800.0)17,18,18                                            SUP 1260
   17 HJB=0.571/(RECB**0.456)                                           SUP 1270
      GOTO19                                                            SUP 1280
   18 HJB=0.346/(RECB**0.382)                                           SUP 1290
   19 HB=(HJB*CPH*GM/CON1)*FACT                                         SUP*1300
      GW=WH/SW                                                          SUP 1310
      GS=SQRTF(GM*GW)                                                   SUP 1320
      RECW=DTO*GS/VISH                                                  SUP 1330
      IF(RECW-800.0)20,21,21                                            SUP 1340
```

```
20    HJW=0.571/(RECW**0.456)                                                SUP 1350
      GOTO22                                                                 SUP 1360
21    HJW=0.346/(RECW**0.382)                                                SUP 1370
   22 HW=(HJW*CPH*GS/CON1)*FACT                                              SUP*1380
      HO=(HB*(1.0-2.0*PW)+HW*(2.0*PW))*BLFH                                  SUP 1390
      HO = HO*GBRL                                                           SUP 1400
      RO(K)=1.0/HO                                                           SUP 1410
23    TH(I+1)=TH(I)-DECT                                                     SUP 1420
      LOP5=0                                                                 SUP 1430
      HC(I+1)=HC(I)-DECH                                                     SUP 1440
      DELPP=0.0                                                              SUP 1450
24    PC(I+1)=PC(I)+DELPP                                                    SUP 1460
      LOP3=0                                                                 SUP 1470
      LOP4=0                                                                 SUP 1480
      TC(I+1)=TC(I)-DECH                                                     SUP 1490
25    CALL SVH(2,PC(I+1),TC(I+1),DUM,HCG)                                    SUP 1500
      EH=ABSF(HC(I+1)-HCG)                                                   SUP 1510
      IF(EH-0.001*HC(I+1))31,31,26                                           SUP 1520
26    TRIAL=TC(I+1)                                                          SUP 1530
      HRIAL=HCG                                                              SUP 1540
      TC(I+1)=TC(I+1)+(HC(I+1)-HCG)*(TC(I)-TC(I+1))/(HC(I)-HCG)              SUP 1550
27    CALLSVH(2,PC(I+1),TC(I+1),DUM,HCG)                                     SUP 1560
      EH=ABSF(HC(I+1)-HCG)                                                   SUP 1570
      IF(EH-0.001*HC(I+1))31,31,28                                           SUP 1580
28    TNEXT=TC(I+1)+(HC(I+1)-HCG)*(TC(I+1)-TRIAL)/(HCG-HRIAL)                SUP 1590
      TRIAL=TC(I+1)                                                          SUP 1600
      HRIAL=HCG                                                              SUP 1610
      TC(I+1)=TNEXT                                                          SUP 1620
      LOP3=LOP3+1                                                            SUP 1630
      IF(LOP3-10)30,30,29                                                    SUP 1640
29    WRITEOUTPUTTAPE51,1015,LOP3                                            SUP 1650
      GOTO80                                                                 SUP 1660
30    GOTO27                                                                 SUP 1670
31    DENOM=(TH(I+1)-TC(I+1))/(TH(I)-TC(I))                                  SUP 1680
      TDEN=ABSF(DENOM-1.0)                                                   SUP 1690
      IF(TDEN-0.05) 32,33,33                                                 SUP 1700
32    DELTLM=0.5E+00*(TH(I+1)-TC(I+1)+TH(I)-TC(I))                           SUP 1710
      GO TO 34                                                               SUP 1720
33    DELTLM=(TH(I+1)-TC(I+1)-TH(I)+TC(I))/LOGF((TH(I+1)-TC(I+1))/(TH(I)SUP 1730
     1-TC(I)))                                                               SUP 1731
```

ORNL TM-2815

Contract No. W-7405-eng-26

General Engineering Division

COMPUTER PROGRAMS FOR MSBR HEAT EXCHANGERS

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APRIL 1971

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operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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COMPUTER PROGRAMS FOR MSBR HEAT EXCHANGERS

Abstract

Three computer programs were developed to make design calculations for the heat exchangers for Molten-Salt Breeder Reactor concepts. They are the program for the primary heat exchangers, PRIMEX; the program for the reheaters, RETEX; and the program for the steam generator superheaters, SUPEX. Each type of exchanger analyzed is described, the basic equations used in each analysis are given, and the logic used in each program is discussed briefly in this report. Flow diagrams, lists of input required and output received, complete program listings, and the nomenclature for the programs as well as example computer input and output for the exchangers described are appended.

1. INTRODUCTION

The concept of a single-fluid Molten-Salt Breeder Reactor (MSBR) with a thermal capacity of 2250 MW and a net electrical output of 1000 MW has some very special heat exchange requirements. In the present conceptual design for the MSBR plant, there are four heat exchangers in the primary system that transfer heat from the molten fluoride fuel-salt mixture to the molten sodium fluoroborate coolant salt. In the secondary system, there are eight reheaters and 16 steam generators that transfer heat from the coolant salt. The manner in which these exchangers were designed to meet the special heat exchange requirements and the computer programs that were developed to calculate the design numbers are described in this report.

The development of MSBR concepts passed through a number of stages during which the plant layout was improved, core configurations were optimized, and physical property data were refined. The first formal study of a MSBR heat exchange system made by the authors was reported in 1967 (GE&C Division Design Analysis Section, "Design Study of a Heat-Exchange System For One MSBR Concept," USAEC Report ORNL TM-1545, Oak

Ridge National Laboratory, September 1967). To analyze one exchanger at each stage of its subsequent development without programming a large portion of the necessary calculations would have meant almost continual repetition of these calculations over a period of many months. With computer programs available, the design for an exchanger could easily be updated for changed capacity, physical properties, temperatures, pressures, etc.

Three such computer programs were developed. One computer program was written to make the design calculations for the primary heat exchanger, and it is the PRIMEX program. This program was modified at one stage of its development to perform the calculations for the steam reheater exchangers. This modified version is the RETEX program. A third computer program was written to perform the design calculations for the steam generator superheater exchangers, and it is the SUPEX program. The design data for each of these three types of exchanger, the basic equations used in each design analysis, and each of the computer programs developed to perform the analysis are described in the following sections of this report. Flow charts for each program, lists of the input required and the output provided by each program, complete program listings, nomenclature lists for each program, and the computer input and output for each type of heat exchanger discussed are appended.

2. PRIMEX, THE PRIMARY HEAT EXCHANGER PROGRAM

There are four primary heat exchangers, which transfer heat from the fuel salt to the coolant salt, in the conceptual design for a single-fluid MSBR. Each of these exchangers has a thermal capacity of 556 MW and each is of the same design. The fuel salt circuits for the primary heat exchangers are in parallel, each having its own fuel pump. The coolant salt from each exchanger is circulated through its own system of two reheater exchangers and four steam generators.

At full design load, the fuel salt enters the top of the primary heat exchanger at a temperature of 1300°F and exits from the bottom at a temperature of 1050°F for return to the reactor. The coolant salt at a temperature of 850°F enters the top of the primary heat exchanger and is directed to the bottom of the exchanger through a central downcomer where it enters the shell side of the exchanger, flows upward in counterflow to the fuel salt, and leaves the top of the exchanger at a temperature of 1150°F. This coolant salt is circulated through the steam reheaters and steam generators where its heat is transferred to the exhaust steam and feedwater, respectively.

The design conditions for the primary heat exchanger were partially dictated by the overall requirements of the MSBR system. The heat load, entrance and exit temperatures of the fuel and coolant salts, and the maximum or desired pressure drops across the shell and tube sides of the exchanger were specified by the operating conditions of the system. Design considerations for the overall system dictated the type of exchanger, arrangement of nozzles to facilitate piping, minimum tube diameter considered to be consistent with fabrication practices, and the limit on the overall length of the exchanger. Certain criteria such as the maximum allowable temperature drop across the tube walls and the need to build in enough tube flexibility to compensate for differential thermal expansion were established by the strength of the materials. Vibration considerations placed limits on flow velocities and the spacing between baffles. In addition, it is highly desirable that the volume of fuel salt be kept at a minimum to lower the doubling time of the reactor.

Within the framework of these requirements and guidelines, a computer program was developed to perform a parameter study and select the design for the primary heat exchanger that employs a minimum volume of fuel salt. The design data and equations discussed in the following subsections were used to develop the computer program for the primary heat exchanger (PRIMEX).

2.1 Description of Primary Heat Exchanger

Each of the four primary heat exchangers is a vertical shell-and-tube type with a single counterflow pass on both the tube and shell sides. Each unit is about 6 ft in diameter and about 22 ft tall, not including the coolant salt U-bend piping at the top. A cross-sectional elevation of a typical primary heat exchanger is illustrated in Fig. 2.1, and the pertinent design data are given in Table 2.1.

The fuel (primary) salt enters the tube side of the primary heat exchanger at the top and flows out the bottom of the exchanger after a single pass through the 3/8-in.-OD tubes. The coolant (secondary) salt enters at the top of the exchanger, flows to the bottom of the exchanger through a central 20-in.-diameter downcomer where it enters the annular shell containing the tubes, flows upward around modified disk and doughnut baffles, and exits through a 28-in.-diameter pipe concentric with the inlet pipe at the top.

The tubes are arranged in concentric rings in the bundle with a constant radial pitch and a circumferential pitch that is as constant as can be obtained. The L-shaped tubes are welded into a horizontal tube sheet at the bottom and into a vertical tube sheet at the top. The toroidal-shaped top head and tube sheet assembly has a significant strength advantage, simplifies the arrangement for coolant-salt flow, and allows the seal weld for the top closure to be located outside the heat exchanger.

To accommodate differential thermal expansion between the shell and tubes, about 4 ft of the upper portion of the tubing is bent into a sine

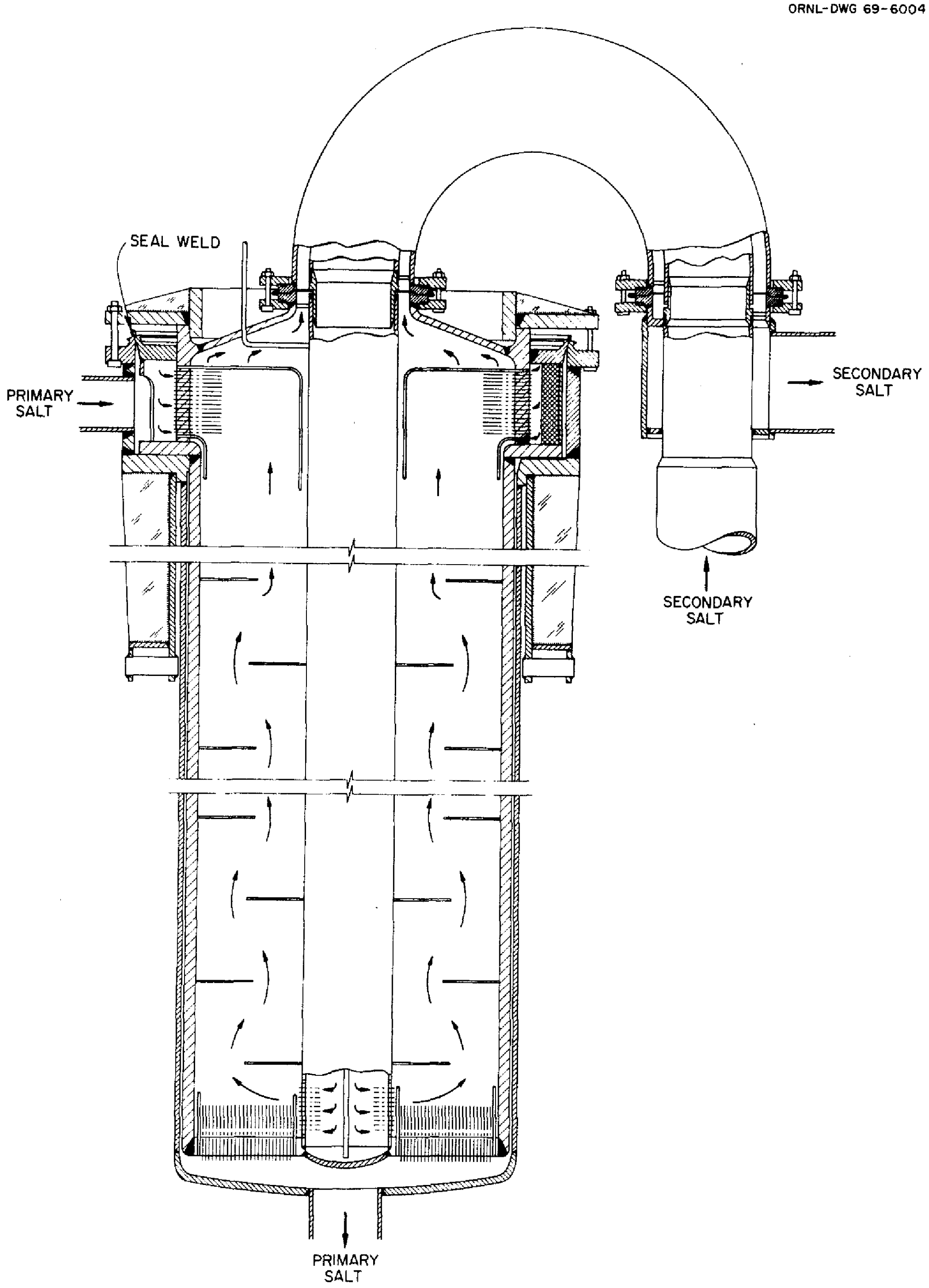

Fig. 2.1. Cross-Sectional Elevation of a Typical MSBR Primary Heat Exchanger.

Table 2.1. Design Data for MSBR Primary Heat Exchanger

Type	Shell-and-tube one-pass vertical exchanger with disk and doughnut baffles
Number required	Four
Rate of heat transfer per unit,	
MW	556.5
Btu/hr	1.9×10^9
Tube-side conditions	
Hot fluid	Fuel salt
Entrance temperature, °F	1300
Exit temperature, °F	1050
Entrance pressure, psi	180
Pressure drop across exchanger, psi	130
Mass flow rate, lb/hr	23.45×10^6
Shell-side conditions	
Cold fluid	Coolant salt
Entrance temperature, °F	850
Exit temperature, °F	1150
Exit pressure, psi	34
Pressure drop across exchanger, psi	116.2
Mass flow rate, lb/hr	17.8×10^6
Tube	
Material	Hastelloy N
Number required	5896
Pitch, in.	0.75
Outside diameter, in.	0.375
Wall thickness, in.	0.035
Length, ft	22.57
Tube sheet	
Material	Hastelloy N
Thickness, in.	4.75
Sheet-to-sheet distance, ft	21.31
Total heat transfer area, ft^2	13,037
Basis for area calculation	Outside of tubes
Volume of fuel salt in tubes, ft^3	67.38
Shell	
Material	Hastelloy N
Thickness, in.	0.5
Inside diameter, in.	68.07
Central tube diameter, in.	20.0
Baffle	
Type	Disk and doughnut
Number	21
Spacing, in.	11.23

Table 2.1 (continued)

Disk outside diameter, in.	54.56
Doughnut inside diameter, in.	45.54
Overall heat transfer coefficient, U, Btu/hr·ft^2·°F	838.3
Tube	
Maximum primary (P) stresses	
Calculated, psi	674
Allowable, psi	3912
Maximum primary and secondary (P + Q) stresses	
Calculated, psi	11,639
Allowable, psi	11,737
Maximum peak (P + Q + F) stresses	
Calculated, psi	13,006
Allowable, psi	25,000

wave configuration. The tubes are held in place by wire lacing in this upper portion of the tube bundle. Since baffling is not employed in this region, the bent-tube portion of the bundle experiences essentially parallel flow and a relatively lower heat transfer performance.

Below the bent-tube region of the bundle, evenly spaced doughnut-shaped baffles are used to hold the tubes in place and to produce cross flow. The baffle spacings and cross-flow velocities are designed to minimize the possibility of flow-induced vibration. The tubes in this baffled region of the heat exchanger have a helical indentation knurled into their surface to enhance the film heat transfer coefficients and thereby reduce the fuel salt inventory in the exchanger. No enhancement of this nature was used in the upper bent-tube region because of present uncertainty about the reliability of tubes that are both bent and indented.

2.2 Design Calculations

Since experience with both the fuel and coolant salts is limited, there was and still is a certain degree of uncertainty associated with the transport properties of salt and its behavior as a heat transfer medium. The design properties of the fuel salt, coolant salt, and of Hastelloy N used in the concept of a single-fluid MSBR and incorporated in the primary heat exchanger computer program are given in Appendix A.

As previously described, the tubes in the baffled portion of the primary heat exchanger are helically indented to improve heat transfer performance. Experiments performed by C. G. Lawson, R. J. Kedl, and R. E. McDonald[1] indicated that this indentation is expected to result in an improvement by a factor of 2 in the tube-side heat transfer coefficient. An enhancement factor of 1.3 for the heat transfer coefficient outside the tubes is suggested by Lawson[2] although no experiments have been done to support this recommendation. The experimental work[1] that was performed was limited to Reynolds numbers greater than 10,000, and there is some uncertainty about the degree of improvement that can be expected for Reynolds numbers of less than 10,000. It was assumed that no improvement can be expected in a truly laminar flow (Reynolds numbers less than 1000), and the improvement expected for the intermediate range was extrapolated by using a method suggested by H. A. McLain.[3] The resulting enhancement factors (EF) are

$$EF_i = 2.0 \text{ and } EF_o = 1.3 \text{ for Reynolds numbers} \geq 10{,}000$$

and

$$EF_i = 1.0 \text{ and } EF_o = 1.0 \text{ for Reynolds numbers} \leq 1000,$$

where

EF_i = enhancement factor inside tube and

EF_o = enhancement factor outside tube (cross flow).

For $1000 <$ Reynolds number $< 10{,}000$,

$$EF_i = 1.0 + \left(\frac{N_{Re} - 1000}{9000}\right)^{1/2} \tag{2.1}$$

and

$$EF_o = 1.0 + 0.3\left(\frac{N_{Re} - 1000}{9000}\right)^{1/2} \tag{2.2}$$

where N_{Re} = the corresponding Reynolds number.

The enhancement factors for heat transfer resulting from the helical indentation of the tubes in the baffled region were assumed to have a proportionate effect on pressure drop. The shell-side pressure drop was calculated by using the procedure reported by O. P. Bergelin et al.,[4] and the tube-side pressure drop was calculated by using the conventional friction-factor method. An overall leakage factor of 0.5 was used for the pressure drop in the shell side of the heat exchanger, and a factor of 0.8 was used in the heat transfer calculations. These leakage factors were selected on the basis of recommendations reported by Bergelin et al.[5] The correct leakage factor, which is dependent upon various clearances between tubes and baffles and between baffles and the shell, will have to be calculated when the actual design for the primary heat exchanger has been completed.

Since molten fluoride salts do not wet Hastelloy N, the containing material of the heat exchanger, it was suspected that the usual heat transfer correlations, which are normally based on experiments with water or petroleum products, might not be valid. However, recent experiments performed by B. Cox[6] indicated that basically the behavior of the fuel salt is similar to that of conventional fluids. The correlations developed by Cox result in heat transfer coefficients somewhat lower than those obtained from the Sieder and Tate correlations for turbulent regions,[7] Hansen's equation for transition regions,[8] and the Sieder and Tate correlations for laminar regions.[7] The correlations used in this study are those based on the data developed by Cox that were recommended by H. A. McLain.[9] These are given in Eqs. 2.3, 2.4, and 2.5.

For completely turbulent flow with Reynolds numbers greater than 12,000,

$$\frac{h_i d_i}{k_i} = 0.217(N_{Re})^{0.8}(N_{Pr})^{1/3}\left(\frac{\mu_b}{\mu_i}\right)^{0.14}(EF_i) \tag{2.3}$$

where

h_i = heat transfer coefficient inside tube, Btu/hr.ft^2.°F,

d_i = inside diameter of tube, ft,

k_i = thermal conductivity of fluid inside tube, Btu/hr·ft·°F,

N_{Re} = Reynolds number,

N_{Pr} = Prandtl number,

μ_b = viscosity at temperature of bulk fluid, lb/hr·ft,

μ_i = viscosity of fluid at temperature of inside surface of tube, lb/hr·ft, and

EF_i = enhancement factor for helically indented tubes given in Eq. 2.1.

Based on the inside diameter of the tube, the Reynolds number

$$N_{Re} = \frac{d_i G_i}{\mu_b}$$

where G_i = mean mass velocity of fluid inside the tube, lb/hr·ft^2. For completely laminar flow with Reynolds numbers less than 2100,

$$\frac{h_i d_i}{k_i} = \left[4.36 + \frac{0.023\left(N_{Re} N_{Pr} \frac{d_i}{\ell}\right)}{1 + 0.0012\left(N_{Re} N_{Pr} \frac{d_i}{\ell}\right)}\right] EF_i \tag{2.4}$$

where ℓ = length of tube from the entrance to the local point, ft. For the intermediate region where 2100 ≤ Reynolds number ≤ 12000,

$$\frac{h_i d_i}{k_i} = 0.089\left[(N_{Re})^{2/3} - 125\right](N_{Pr})^{1/3}\left[1 + \frac{1}{3}\left(\frac{d_i}{\ell}\right)^{2/3}\right]\left(\frac{\mu_b}{\mu_i}\right)^{0.14}\left(EF_i\right) . \tag{2.5}$$

The pressure drop inside the tubes was calculated by using the expression

$$\Delta P_i = \frac{4fL}{d_i}\left(\frac{G_i^2}{2\rho_i g_c}\right)(EF_i) \tag{2.6}$$

where

f = friction factor,

L = length of tube, ft,

d_i = inside diameter of tube, ft,

G_i = mean mass velocity of fluid inside tube, lb/hr·ft^2,

ρ_i = density of fluid inside tube, lb/ft^3,

g_c = dimensional conversion factor = 4.18×10^8 lb$_m$·ft/lb$_f$·hr^2, and

EF_i = enhancement factor for helically indented tubes given in Eq. 2.1.

The friction factor for turbulent flow ($N_{Re} > 2100$) is given by the expression

$$f = 0.0014 + 0.125(N_{Re})^{-0.32} \ , \qquad (2.7)$$

and the friction factor for laminar flow ($N_{Re} < 2100$) is given by the expression

$$f = \frac{16}{N_{Re}} \ . \qquad (2.8)$$

The heat transfer coefficient across the tube wall is given by the expression

$$h_w = \left(\frac{k}{d_o t}\right) \frac{d_o - d_i}{\ln \frac{d_o}{d_i}} \ , \qquad (2.9)$$

where

k = thermal conductivity, Btu/hr·ft·°F,

d_o = outside diameter of tube, ft,

t = wall thickness, ft, and

d_i = inside diameter of tube, ft.

No experiments have been performed to date to develop correlations for the heat transfer behavior of a sodium fluoroborate coolant salt in the shell side of the heat exchanger. The correlation developed by O. P. Bergelin et al.[4] was used for the baffled region of the MSBR primary heat exchanger, and the correlation developed by D. A. Donohue[10] was used for the unbaffled region.

Although selected as being the most representative available for the baffled region, Bergelin's correlation[4] is strictly for cross flow and his data were based on work with half-moon shaped baffles with straight edges. Since disk and doughnut baffles are used in the MSBR primary heat exchanger, the adaptation of Bergelin's data involved certain interpretations in determining the cross-sectional areas involved. The correlation for cross flow was also modified by the introduction of a correction factor. This correction factor is dependent upon the degree of actual cross flow that exists as determined by the ratio between the baffle spacing and the annular thickness of the vessel. Data from Bergelin's original experiment[4] were used to estimate the value of the correction factor, which is expressed as

$$BCF = 0.77\left(\frac{X}{Y}\right)^{-0.138} \tag{2.10}$$

where

BCF = correction factor for shell-side heat transfer coefficient as proposed by Bergelin,[4]

X = baffle spacing (as illustrated in Fig. 2.2), ft, and

Y = radial distance from center of window to center of opposing window (as illustrated in Fig. 2.2), ft.

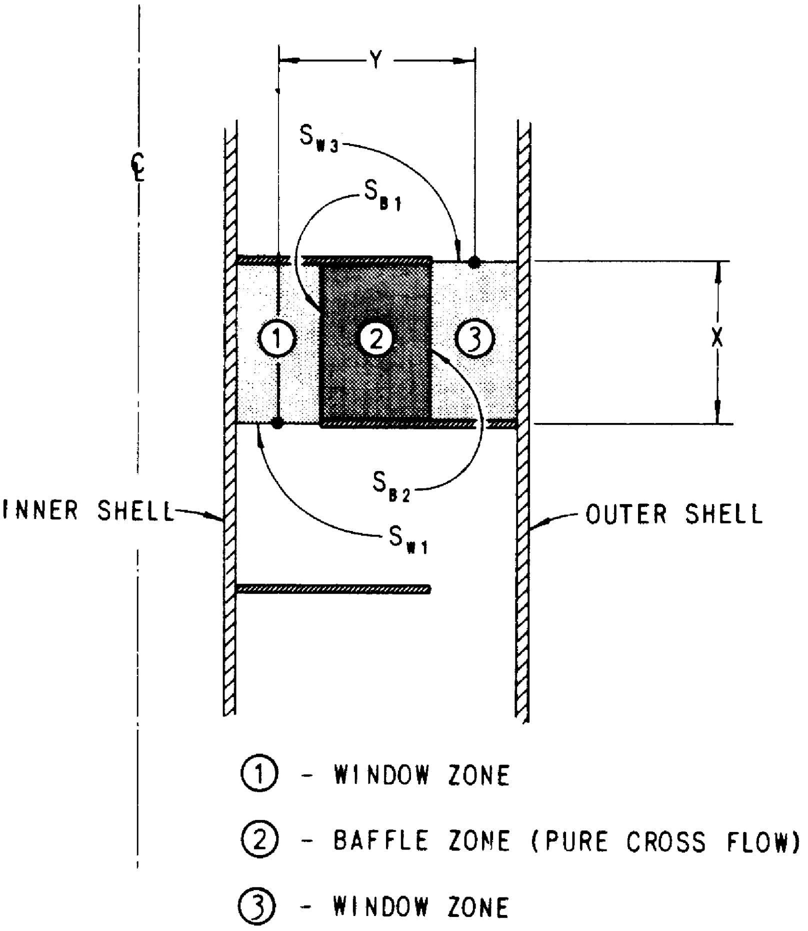

Fig. 2.2. Zones of Flow Between Two Baffles in the Shell Side of the MSBR Primary Heat Exchanger.

In the method advanced by Bergelin,[4] the region between two baffles is considered as three parts: one pure cross-flow zone between two window zones, as illustrated in Fig. 2.2. The mass velocity in each zone is based on the effective area of each zone. In a window zone, the effective area is given by the expression

$$S_z = (S_w S_B)^{1/2} \tag{2.11}$$

where

S_w = free cross-sectional area in baffle window, ft^2, and
S_B = free cross-sectional area for cross flow between tubes applied at lip of the baffle, ft^2.

The effective area of the pure cross-flow zone is given by the expression

$$S_m = 0.5(S_{B_1} + S_{B_2}) \tag{2.12}$$

where the indices 1 and 2 indicate the sides of the pure cross-flow zone. Based on this definition of the areas or zones used to calculate the mass velocity, the Reynolds number for each zone is determined from the expression

$$N_{Re} = \frac{d_o G}{\mu_b} \tag{2.13}$$

where

d_o = outside diameter of the tube, ft,
G = mass velocity of the fluid outside the tubes, lb/hr·ft^2, and
μ_b = viscosity at temperature of bulk fluid, lb/hr·ft.

The relationship between the Reynolds number for each flow zone and an appropriate heat transfer factor (J) is developed in Bergelin's method.[4] The heat transfer factor for the window zone is determined from the expression

$$J_w = \frac{h_w}{C_p G_m}\left(\frac{C_p \mu_b}{k}\right)^{2/3}\left(\frac{\mu_s}{\mu_b}\right)^{0.14} (EF_o)(BCF)(LF) \tag{2.14}$$

where

h_w = heat transfer coefficient for window zone, Btu/hr·ft^2·°F,
C_p = specific heat, Btu/lb·°F,
G_m = mean mass velocity of fluid, lb/hr·ft^2,

k = thermal conductivity, Btu/hr·ft·°F,

μ_b = viscosity at temperature of bulk fluid, lb/hr·ft,

μ_s = viscosity of fluid at temperature of wall surface, lb/hr·ft,

EF_o = enhancement factor outside helically indented tube given by Eq. 2.2,

BCF = correction factor for shell-side heat transfer coefficient given by Eq. 2.10, and

LF = leakage factor for heat transfer taken as 0.8.

The heat transfer factor for the cross-flow zone (J_B) is determined from the expression

$$J_B = \frac{h_B}{C_p G_B}\left(\frac{C_p \mu_b}{k}\right)^{2/3}\left(\frac{\mu_s}{\mu_b}\right)^{0.14}(EF_o)(BCF)(LF) \; . \tag{2.15}$$

Equations 2.16 and 2.17 were derived from the graph of J versus N_{Re} given in Ref. 4 to determine the values of J. The values of J determined from Eqs. 2.16 and 2.17 were then used in Eqs. 2.14 and 2.15 to determine the heat transfer coefficients for the window zones and the cross-flow zone (h_w and h_B).

$$\text{For } 800 \leq N_{Re} \leq 10^5, \; J = 0.346(N_{Re})^{0.382} \tag{2.16}$$

$$\text{For } 100 \leq N_{Re} \leq 800, \; J = 0.571(N_{Re})^{0.456} \tag{2.17}$$

The values of the heat transfer coefficients for the window zones (h_{w1} and h_{w2}) and the value for the cross-flow zone (h_B) were then combined in Eq. 2.18 to determine the total heat transfer coefficient for the region between two baffles.

$$h_t = h_B a_B + h_{w1} a_{w1} + h_{w2} a_{w2} \; , \tag{2.18}$$

where a = the area of heat transfer surface in each zone, ft^2/ft.

The data reported by D. A. Donohue[10] were used for heat transfer calculations involving parallel flow on the shell side of the MSBR primary heat exchanger. The heat transfer coefficient outside the tubes is given by the expression

$$h_o = 0.128\left(\frac{k_o}{d_o}\right)(12d_{eq})^{0.6}\left(\frac{d_o G}{\mu_b}\right)^{0.6}\left(\frac{C_p \mu_b}{k_o}\right)^{0.33}\left(\frac{\mu_b}{\mu_s}\right)^{0.14} \tag{2.19}$$

where

k_o = thermal conductivity of fluid outside tubes, Btu/hr·ft·°F,
d_o = outside diameter of tube, ft,
d_{eq} = equivalent diameter, ft,
G = mass velocity of fluid outside tubes, lb/hr·ft^2,
μ_b = viscosity at temperature of bulk fluid, lb/hr·ft,
C_p = specific heat, Btu/lb·°F, and
μ_s = viscosity of fluid at temperature of wall surface, lb/hr·ft.

The overall heat transfer coefficient was then calculated by using the expression

$$U_o = \frac{1}{\frac{1}{h_o} + \frac{1}{h_W} + \frac{1}{h_i}\left(\frac{d_o}{d_i}\right)} , \tag{2.20}$$

where h_o, h_W, and h_i are the shell-side, wall, and tube-side heat transfer coefficients, respectively.

The shell-side pressure drops in the baffled region of the MSBR primary heat exchanger were calculated by using the equations reported by O. P. Bergelin et al.[4] The pressure drop across the cross-flow zone is given by the expression

$$\Delta P_{\text{cross flow}} = 0.6 r_B \rho \left(\frac{V_m^2}{2g_c}\right) (\text{PLF})(\text{EF}) \tag{2.21}$$

where

r_B = number of cross-flow restrictions,
ρ = density of fluid, lb/ft^3,
V_m = cross-flow velocity of fluid (based on effective area S_m given by Eq. 2.12), ft/sec,
g_c = dimensional conversion factor = 32.2 lb$_m$·ft/lb$_f$·sec^2,
PLF = pressure drop leakage factor taken as 0.5, and
EF = enhancement factor outside helically indented tubes taken as 1.3.

The pressure drop across the window zone is given by the expression

$$\Delta P_{\text{window}} = (1 + 0.6 r_w)\left(\frac{\rho V_z^2}{2g_c}\right)(\text{PLF})(\text{EF}) \tag{2.22}$$

where

r_w = number of restrictions in the window zone and

V_z = mean flow velocity (based on the effective area S_z given by Eq. 2.11), ft/sec.

The number of restrictions was interpreted as being the number of rows of tubes in the direction of cross flow. The full number was used for the cross-flow zone, while only half of the number of rows was used for each of the window zones. The shell-side pressure drop in the upper bent-tube region of the exchanger was taken as being approximately equal to the pressure drop across one baffled zone.

2.3 Description of PRIMEX

The computer program for the MSBR primary heat exchanger, PRIMEX, is presented in Appendix B. In this program, each zone between two baffles was considered as one increment length. The calculations are begun on the hot side of the heat exchanger, and increments are added until a complete heat balance is achieved. The dependence of each of the physical properties on temperature is given as an empirical equation, and these equations are incorporated in the main program. If any of these equations are changed, the appropriate data card must be replaced. The physical property data as well as the other input data required for the PRIMEX program are listed in Appendix B. A list of the output data received from the computer is also presented.

A stress analysis subroutine, TUBSTR, is incorporated in the main program. This subroutine performs a preliminary stress analysis of the tubes with the assumption that the maximum tube stress will occur in the upper bent-tube region of the heat exchanger. Pressure stresses, stresses resulting from thermal expansion, and stresses resulting from the thermal gradient across the tube wall are considered. The primary and secondary stresses are computed, and these computed values are compared with the allowable values given in Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code. A second subroutine, LAGR, is used for interpolation of values from a given table. The complete listing for the main program together with its two subroutines is given in Appendix B.

To illustrate the use of the PRIMEX program, the computer input data for the MSBR primary heat exchanger discussed in Subsection 2.1 and the output data printed by the computer are included in Appendix B. The time required for a typical IBM 360/91 computer run of this program is about 2 minutes.

2.4 Evaluation of PRIMEX

It is believed that the use of the PRIMEX computer program will result in a primary heat exchanger whose volume of fuel salt will be kept to a minimum and whose design will be more reliable than can be achieved with normal hand calculations. Variations in physical properties and complicated geometries are handled easily, and an extensive parameter study can be made in a very short time.

However, the output of a computer program cannot be better than the input. The input data which have a significant effect on the design of the heat exchanger are the physical properties of the fuel and coolant salts, the heat transfer correlations used, the enhancement factors assumed for the helically indented tubes, and the leakage factors associated with fabrication clearances. The average deviations in the physical properties of the fuel and coolant salts presently used in the program are those reported by J. R. McWherter.[11] The most notable uncertainties in the physical property values presently are associated with the viscosity and thermal conductivity of the fuel salt. The average deviation for the fuel-salt heat transfer correlation is reported[6] as being about 5.7%. The deviation or error resulting from the use of Bergelin's correlation[4] is not certain, but shell-side heat transfer coefficients normally have a deviation of about 25%. The leakage factor deviation for the pressure drop might be about 20%, and the leakage factor deviation for the shell-side heat transfer coefficient might be about 10%. The enhancement factor deviation might be about 15%.

The two extreme cases were checked. All of the pessimistic values were used in one case, and all of the optimistic values were used in the other case. The result was a maximum estimated deviation in the overall heat transfer area (or volume of fuel salt) of +38% (additional area required) for the pessimistic case and -28% (less area required) for the optimistic case.

3. RETEX, THE STEAM REHEATER EXCHANGER PROGRAM

The coolant salt circulating system in the conceptual design of a single-fluid MSBR consists of four independent loops, each containing salt circulating pumps, steam generators, steam reheaters, and the shell side of one of the four primary heat exchangers. There are two steam reheater exchangers, which transfer heat from the coolant salt to preheated exhaust steam from the high-pressure turbine, in each coolant salt loop; with a total of eight reheaters to meet the total steam reheating requirement of approximately 5.1×10^6 lb/hr. Each reheater is of the same design, and each has a thermal capacity of about 36.6 MW.

At full design load, the coolant salt from the primary heat exchanger enters the shell side of the reheater at a temperature of 1150°F and exits at a temperature of 850°F for return to the primary heat exchanger. The preheated exhaust steam from the high-pressure turbine enters the tube side of the reheater at a temperature of 650°F, flows through the tubes in counterflow to the coolant salt, and leaves the reheater at a temperature of 1000°F for delivery to the intermediate-pressure turbine.

Basically, the steam reheater exchangers must meet the same system requirements prescribed for the primary heat exchangers that were discussed in Section 2 of this report. However, since no fuel salt is involved, the desirability of keeping the fluid volume at a minimum is not a critical factor in the design of the reheater. In addition, the lower heat load and average temperatures permit more freedom in designing the geometry of the reheater to avoid problems associated with vibration or overstress.

Since the design for the steam reheater exchanger is similar to that for the primary heat exchanger, an early version of the basic PRIMEX computer program was modified to fit the requirements of the steam reheater, thereby becoming the RETEX program. The design data and equations used to develop the RETEX computer program are discussed in the following subsections.

3.1 Description of Steam Reheater

Each of the eight steam reheater exchangers is a horizontal shell-and-tube unit with a single counterflow pass on both the shell and tube sides. Each unit is about 30 ft long and has an outside diameter of 22 in. A typical reheater is illustrated in Fig. 3.1.

The preheated exhaust steam enters the tube side of the reheater at a pressure of about 580 psi, flows through the 0.75-in.-OD tubes, and exits at a pressure of 550 psi. There are 400 straight tubes arranged in a triangular-pitch array in each reheater. The surfaces of these tubes are not helically indented to enhance heat transfer, as are those in the primary heat exchanger.

The coolant salt enters the shell side of the reheater at a pressure of about 228 psi, flows around disk and doughnut baffles in counterflow to the exhaust steam, and exits at a pressure of 168 psi. Other pertinent design data for the steam reheater exchanger are given in Table 3.1.

Table 3.1. Design Data for MSBR Steam Reheater Exchanger

Type	Straight shell-and-tube one-pass horizontal unit with disk and doughnut baffles
Number required	Eight
Rate of heat transfer per unit,	
MW	36.6
Btu/hr	1.25×10^8
Shell-side conditions	
Hot fluid	Coolant salt
Entrance temperature, °F	1150
Exit temperature, °F	850
Entrance pressure, psi	228
Exit pressure, psi	168
Pressure drop across exchanger, psi	59.52
Mass flow rate, lb/hr	1.16×10^6
Tube-side conditions	
Cold fluid	Exhaust steam
Entrance temperature, °F	650
Exit temperature, °F	1000
Entrance pressure, psi	580
Exit pressure, psi	550
Pressure drop across exchanger, psi	29.85
Mass flow rate, lb/hr	6.41×10^5

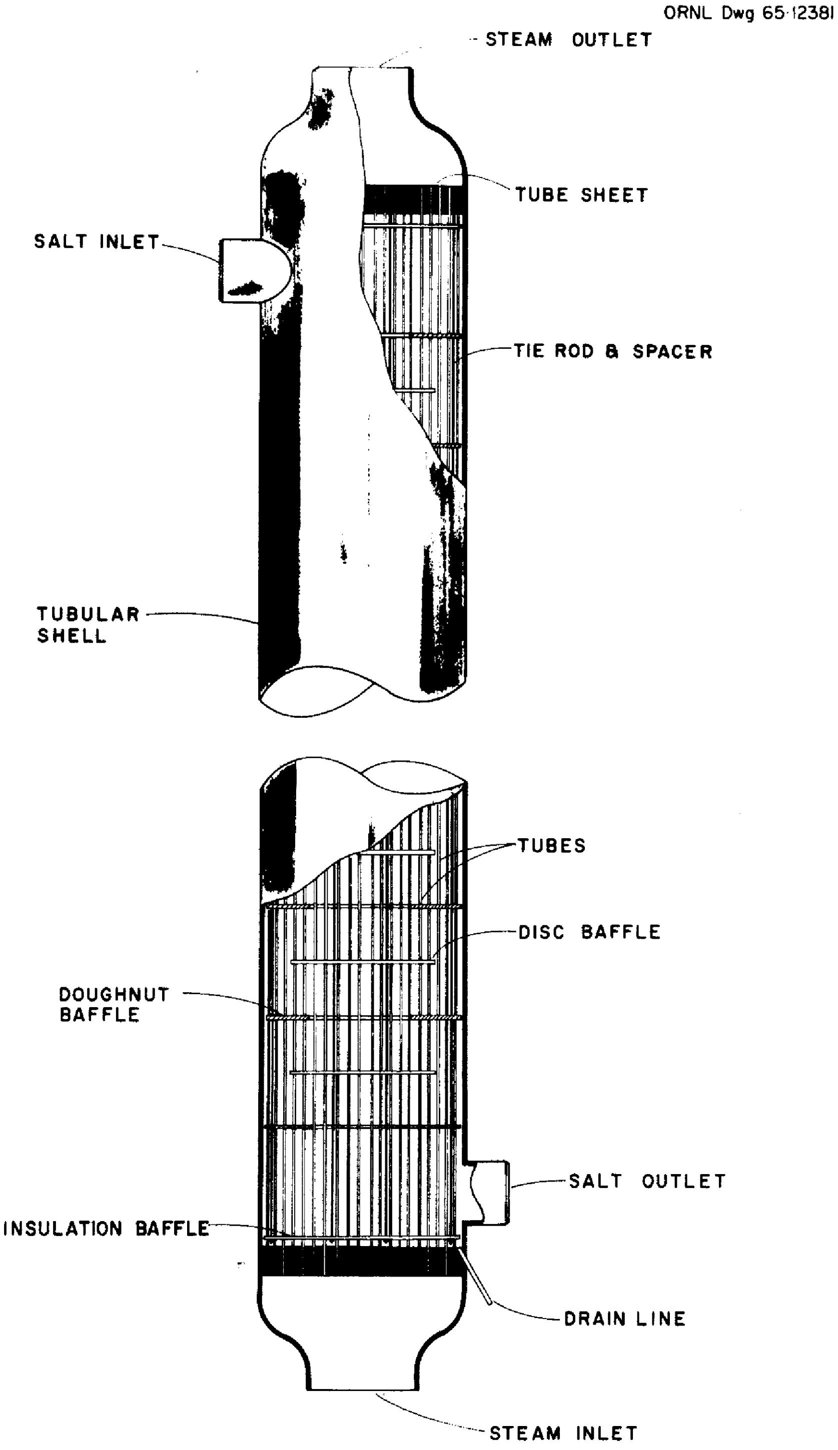

Fig. 3.1. Typical MSBR Steam Reheater Exchanger.

Table 3.1 (continued)

Tube	
Material	Hastelloy N
Number required	400
Pitch, in.	1.0 (triangular)
Outside diameter, in.	0.75
Wall thickness, in.	0.035
Length (tube sheet to tube sheet), ft	30.26
Tube sheet material	Hastelloy N
Total heat transfer area, ft^2	2376
Basis for area calculation	Outside of tubes
Shell	
Material	Hastelloy N
Thickness, in.	0.5
Inside diameter, in.	21.2
Baffle	
Type	Disk and doughnut
Number	21 each
Spacing, in.	8.65
Disk outside diameter, in.	17.75
Doughnut inside diameter, in.	11.61
Overall heat transfer coefficient, U, Btu/hr·ft^2	306
Tube	
Maximum primary (P_m) stress	
Calculated, psi	4582
Allowable, psi	13,000
Maximum primary and secondary ($P_m + Q$) stress	
Calculated, psi	14,090
Allowable, psi	39,000
Shell	
Maximum primary (P_m) stress	
Calculated, psi	5016
Allowable, psi	9500
Maximum primary and secondary ($P_m + Q$) stress	
Calculated, psi	14,550
Allowable, psi	28,500

3.2 Design Calculations

When developing the computer program RETEX to analyze the steam reheater exchanger, the properties of the steam were assumed to be essentially constant along the length of the exchanger even though it was recognized that some gain in the reliability of the estimates could have been realized by incorporating the steam properties as a function of pressure and temperature. The usual Dittus-Boelter equations were used for the film heat transfer coefficient on the tube side of the exchanger. The other procedures and correlations used in the analysis of the reheater are basically the same as those used for the primary heat exchanger discussed in Subsection 2.2 of this report.

Manual computational methods were used to determine the stresses in the steam reheater exchanger. This preliminary stress analysis was based on the requirements of Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code; and the calculated values are compared with the allowable values in Table 3.1. However, a complete stress analysis as required by Section III of the ASME Boiler and Pressure Vessel Code has not been made.

3.3 Description of RETEX

The RETEX program, a modified version of the PRIMEX program, was used to analyze the steam reheater exchanger. In the RETEX program, each zone between two baffles is considered as one increment length. The calculations are begun on the hot side of the exchanger, and increments are added until a complete heat balance is achieved. The physical property equations for the fuel salt in the PRIMEX program are replaced with the physical property data for the exhaust steam in the RETEX program, and these properties are considered as being essentially constant along the length of the exchanger. The physical properties of the coolant salt are evaluated at the average temperature of each increment. The dependence of the physical properties on temperature is presently expressed in the form of empirical equations incorporated in the main program. If any of these equations are changed, the appropriate data card must be replaced.

The RETEX computer program differs from the PRIMEX computer program in that

1. the reheater tubes are not helically indented to enhance heat transfer, and no enhancement factors are used in the RETEX program;
2. the reheater tubes are arranged in a triangular-pitch array rather than in concentric circles, and certain geometric calculations are therefore made differently in the RETEX program;
3. none of the reheater tubes are bent in a sine-wave configuration to accommodate differential thermal expansion; and
4. no stress analysis subroutines are included in the RETEX program (stresses were calculated by hand).

The computer program for the MSBR steam reheater exchanger, RETEX, is given in Appendix C. A simplified outline of the program in block-diagram form, a list of the input data required, a list of the output received from the computer, and a complete listing of the main program are presented. The RETEX program terms which differ from those of the PRIMEX program are defined. To illustrate the use of the RETEX program, the computer input data for the steam reheater exchanger discussed in Subsection 3.1 and the output printed by the computer are also included in Appendix C. The time required for a typical IBM 360/91 computer run of this program is about 1 minute.

3.4 Evaluation of RETEX

Confidence in the design calculations for the steam reheater exchanger is greater than that in the calculations for the primary heat exchanger because the characteristics of steam are more familiar than those of the fuel salt and because no enhancement factors are involved. Vibration problems are not likely to be encountered in the steam reheater because velocities are less than 6.5 fps and the tubes are supported by baffles with a relatively close spacing.

The uncertainties associated with the coolant salt are involved in the RETEX program, and the deviations applied for the primary heat exchanger (discussed in Subsection 2.4) are also applicable to the steam reheater. Again, two extreme cases were considered. All the pessimistic values were used in one case, and all the optimistic values were used in the other. The result was a maximum estimated deviation in the overall heat transfer area of +23% (additional area required) for the pessimistic case and -13% (less area required) for the optimistic case.

4. SUPEX, THE STEAM GENERATOR SUPERHEATER PROGRAM

There are four steam generator superheater exchangers, which transfer heat from the coolant salt to feedwater, in each of the four coolant salt circulating loops of the MSBR concept. The total steam generation requirement, which includes that needed for the feedwater and preheating the exhaust steam, of about 10 × 10^6 lb/hr is provided by the 16 steam generators, each having a thermal capacity of about 121 MW.

These exchangers serve as both steam generators and superheaters. They are operated in parallel with respect to the coolant salt and steam flows, and they are identical in design and operation. At full design load, preheated feedwater enters the exchanger at a temperature of 700°F, and the supercritical steam exits at a temperature of 1000°F. The coolant salt enters the exchanger at a temperature of 1150°F and exits at a temperature of 850°F for return to the primary heat exchanger.

The factors influencing the design of the steam generator exchanger are partially dependent upon the requirements for the overall MSBR system. The exit temperature and pressure of the steam were dictated by the steam power system selected. The inlet temperature of the steam was determined by considerations relative to the liquidus temperature of the salt and the rapid increase in heat capacity of the supercritical water at temperatures above 700°F. The inlet and exit temperatures of the coolant salt, the pressure drop, and the total heat to be transferred were dictated by the requirements for the reactor and primary heat exchange systems. In addition to these system requirements, the design for the steam generator exchanger must satisfy stress, stability, and space requirements.

Because of the marked changes in the physical properties of the feedwater as the temperature is raised above the critical temperature at supercritical pressures, the heat transfer and flow characteristics vary considerably throughout the exchanger. The SUPEX computer program was developed to account for these changes by making the heat transfer and pressure drop calculations for incremental tube lengths. The design data and equations used to develop this computer program for analysis of the steam generator exchanger are discussed in the following subsections.

4.1 Description of Steam Generator

Each of the 16 steam generator superheater exchangers is a U-tube, U-shell unit mounted horizontally with one leg above the other. Each has a single pass on the shell and tube sides with the flow in one side counter to that in the other. The overall length of each exchanger is about 40 ft, and the overall height from the feedwater inlet plenum to the steam outlet plenum is about 12 ft. A typical steam generator is shown in Fig. 4.1.

Fig. 4.1. Typical MSBR Steam Generator Superheater Exchanger.

The feedwater enters the tube side of the exchanger at a pressure of 3754 psi, flows through the 0.50-in.-OD tubes, and the supercritical steam exits at a pressure of 3600 psi. The coolant salt enters the shell side of the exchanger at a pressure of 233 psi, circulates in counterflow to the supercritical fluid around segmental baffles, and exits at a pressure of 172 psi. Segmental baffles are used to improve the heat transfer coefficient for the salt film and to minimize salt stratification. A baffle on the shell side of each tube sheet provides a stagnant layer of salt to help reduce stresses resulting from temperature gradients across the tube sheets.

Location of the steam generator exchanger in a horizontal position reduces the possibility of unstable flow conditions for the supercritical fluid in the tubes. The U-tubes are arranged in a triangular-pitch array and the ends of the tubes are turned 90° to equalize the lengths of the tubes in the exchanger. This equalization of tube lengths further reduces the possibility of unstable flow conditions. The pertinent design data for the steam generator exchanger are given in Table 4.1.

Table 4.1. Design Data for MSBR Steam Generator Superheater Exchanger

Type	U-shell, U-tube one-pass horizontal unit with cross-flow baffles
Number required	16
Rate of heat transfer per unit,	
MW	121
Btu/hr	4.13×10^8
Shell-side conditions	
Hot fluid	Coolant salt
Entrance temperature, °F	1150
Exit temperature, °F	850
Entrance pressure, psi	233.0
Exit pressure, psi	172.0
Pressure drop across exchanger, psi	61.0
Mass flow rate, lb/hr	3.82×10^6

Table 4.1 (continued)

Tube-side conditions	
Cold fluid	Supercritical fluid
Entrance temperature, °F	700
Exit temperature, °F	1000
Entrance pressure, psi	3754
Exit pressure, psi	3600
Pressure drop across exchanger, psi	154
Mass flow rate, lb/hr	6.33×10^5
Mass velocity, $lb/hr \cdot ft^2$	2.47×10^6
Tube	
Material	Hastelloy N
Number required	393
Pitch, in.	0.875 (triangular)
Outside diameter, in.	0.50
Wall thickness, in.	0.077
Length (tube sheet to tube sheet), ft	76.4
Tube sheet	
Material	Hastelloy N
Thickness, in.	4.5
Total heat transfer area, ft^2	3929
Basis for area calculation	Outside of tubes
Shell	
Material	Hastelloy N
Wall thickness, in.	0.375
Inside diameter, in.	18.25
Baffle	
Type	Cross flow
Spacing, ft	4.02
Number of spaces	19

4.2 Design Calculations

The heat transfer coefficient for the supercritical fluid film on the inside of the tube walls is determined by using the correlation reported by H. S. Swenson et al.[12] This correlation is given in Eq. 4.1.

$$\frac{h_i d_i}{k_i} = 0.00459\left(\frac{d_i G}{\mu_i}\right)^{0.923}\left[\frac{H_i - H_b}{T_i - T_b}\left(\frac{\mu_i}{k_i}\right)\right]^{0.613}\left(\frac{v_b}{v_i}\right)^{0.231} , \qquad (4.1)$$

where

h_i = heat transfer coefficient inside tube, Btu/hr·ft^2·°F,

d_i = inside diameter of tube, ft,

k_i = thermal conductivity of fluid inside tube, Btu/hr·ft^2·°F per ft,

G = mass velocity of fluid, lb/hr·ft^2,

μ_i = viscosity of fluid at temperature of inside surface of tube, lb/hr·ft,

H_i = enthalpy at temperature of inside surface of tube, Btu/lb,

H_b = enthalpy at temperature of bulk fluid, Btu/lb,

T_i = temperature of fluid at inside surface of tube, °F,

T_b = temperature of bulk fluid, °F,

v_b = specific volume of bulk fluid, ft^3/lb, and

v_i = specific volume of fluid inside tube, ft^3/lb.

The values of specific volume and enthalpy for the supercritical fluid under various conditions of pressure and temperature are taken from data reported by J. H. Kennan and F. G. Keyes.[13] A table look-up subroutine is included in the SUPEX computer program for determination of these values. The values of thermal conductivity and viscosity for the supercritical fluid are determined from data reported by E. S. Nowak and R. J. Grosh.[14] These data were represented by Eqs. 4.2 and 4.3 in the SUPEX computer program.

$$\mu = 0.02191\left(\frac{v}{v - 0.012}\right)^2\left(\frac{T + 460}{492}\right)^{1.5}\left(\frac{1478}{T + 1446}\right) \tag{4.2}$$

and

$$k = (1.093 \times 10^{-6})(T + 460)^{1.45} + (28.54 \times 10^{-4})v^{-1.25}, \tag{4.3}$$

where

v = specific volume, ft^3/lb, and

T = temperature of fluid, °F.

The heat transfer coefficient for the salt film on the outside surface of the tubes is determined by using the method proposed by O. P. Bergelin et al.[4,5] The experimental data[4] are presented as correlations between a heat transfer factor (J) and the Reynolds number, with the Reynolds number defined by the expression

$$N_{Re} = \frac{d_o G}{\mu_b} \tag{4.4}$$

where

d_o = outside diameter of tube, ft,
G = mass velocity of the fluid, lb/hr·ft^2, and
μ_b = viscosity at temperature of bulk fluid, lb/hr·ft.

The shell side of the steam generator exchanger is divided into two types of flow regions by the segmental baffles. These are the cross-flow and window regions, and the heat transfer factor is determined for each. The heat transfer factor for the cross-flow region (J_B) is given by the expression

$$J_B = \frac{h_B}{C_p G_B}\left(\frac{C_p \mu_b}{k}\right)^{2/3}\left(\frac{\mu_o}{\mu_b}\right)^{0.14} \tag{4.5}$$

where

h_B = heat transfer coefficient for cross-flow region, Btu/hr·ft^2·°F,
C_p = specific heat, Btu/lb·°F,
G_B = mass velocity of fluid in cross-flow region, lb/hr·ft^2,
μ_b = viscosity at temperature of bulk fluid, lb/hr·ft,
k = thermal conductivity, Btu/hr·ft·°F, and
μ_o = viscosity of fluid at temperature of outside surface of tube, lb/hr·ft.

The heat transfer factor for the window region is given by the expression

$$J_w = \frac{h_w}{C_p G_m}\left(\frac{C_p \mu_b}{k}\right)^{2/3}\left(\frac{\mu_o}{\mu_b}\right)^{0.14} \tag{4.6}$$

where

h_w = heat transfer coefficient for window region, Btu/hr·ft^2·°F, and
G_m = mean mass velocity, lb/hr·ft^2.

The mean mass velocity is given by the expression

$$G_m = \left(G_B G_w\right)^{1/2} , \tag{4.7}$$

where G_w = mass velocity of fluid in window region, lb/hr·ft^2. Equations for determining values of J were fitted to the graph of J versus N_{Re} given in Fig. 11 of Ref. 4 for use in the SUPEX computer program. The values of J given by Eqs. 4.8 and 4.9 are used in Eqs. 4.5 and 4.6 to determine the heat transfer coefficients for the cross-flow and window regions (h_B and h_w).

$$\text{For } 100 \leq N_{Re} \leq 800, \quad J = 0.571(N_{Re})^{-0.456} \tag{4.8}$$

and

$$\text{For } 800 \leq N_{Re} \leq 10^5, \quad J = 0.346(N_{Re})^{-0.382} \tag{4.9}$$

In Bergelin's method,[4] the heat transfer coefficient for the shell side of the exchanger is a linear combination of the heat transfer coefficients for the cross-flow and window regions weighted by the amount of heat transfer surface in each region and corrected for bypass leakage. Because of the large baffle-spacing-to-shell-diameter ratio (approximately 2.7) required for the steam generator exchanger, an additional correction factor is applied to the shell-side heat transfer coefficient. The total shell-side heat transfer coefficient (h_o) is given by the expression

$$h_o = 0.77B\left(\frac{2y}{X}\right)^{0.138}\left(\frac{h_B a_B + h_w a_w}{a_B + a_w}\right) , \tag{4.10}$$

where

B = bypass leakage factor recommended by Bergelin,[4]

y = distance from the center line of the shell to the centroid of the segmental window area, ft,

X = baffle spacing, ft,

h_B = heat transfer coefficient for cross-flow region, Btu/hr·ft^2·°F,

a_B = area of heat transfer surface in cross-flow region per unit length, ft^2/ft,

h_w = heat transfer coefficient for window region, Btu/hr·ft^2·°F, and

a_w = area of heat transfer surface in window region per unit length, ft^2/ft.

The values of specific heat and thermal conductivity for the coolant salt are treated as constants, independent of temperature, and are included in the input information for the SUPEX computer program. The density and viscosity of the salt are treated as functions of temperature as determined by Eqs. 4.11 and 4.12.

$$\rho = 141.38 - 0.02466(T) \tag{4.11}$$

and

$$\mu = 0.2122 \exp\left[\frac{4032}{(T + 460)}\right] , \tag{4.12}$$

where

ρ = density of coolant salt, lb/ft^3,
T = temperature of salt, °F, and
μ = viscosity of salt, lb/hr·ft.

The thermal resistance of the tube wall is calculated for each increment of tube length by using the thermal conductivity of Hastelloy N evaluated at the average temperature of the tube wall for each particular increment. The thermal resistance of the tube wall is given by the expression

$$R_W = \frac{d_o}{2k_W}\left(\ln \frac{d_o}{d_i}\right) , \tag{4.13}$$

where

R_W = thermal resistance of tube wall, hr·ft^2·°F/Btu,
d_o = outside diameter of tube, ft,
k_W = thermal conductivity of tube wall, Btu/hr·ft·°F, and
d_i = inside diameter of tube, ft.

The thermal conductivity of the tube wall is given by the expression

$$k_W = 0.006375T_W + 4.06 \tag{4.14}$$

where T_W = mean temperature of the tube wall, °F. The total thermal resistance, based on the outer surface area of the tube, is given by the expression

$$R_t = \frac{d_o}{h_i d_i} + \frac{1}{h_o} + R_W . \tag{4.15}$$

The heat transferred per increment of exchanger length (ΔQ) is given by the expression

$$\Delta Q = \frac{\pi d_o n(\Delta L)(\Delta T_m)}{R_t} , \tag{4.16}$$

where

d_o = outside diameter of tube, ft,
n = number of tubes,
ΔL = increment of tube length, ft,
ΔT_m = mean temperature difference between coolant salt and supercritical fluid for the particular increment, °F, and
R_t = total thermal resistance given by Eq. 4.15.

The pressure drop per increment of tube length for the supercritical fluid inside the tubes is given by the expression

$$\Delta P = \frac{4f(\Delta L)}{144d_i}\left(\frac{G^2}{2g_c\rho}\right) , \tag{4.17}$$

where

f = friction factor,
ΔL = increment of tube length, ft,
d_i = inside diameter of tube, ft,
G = mass velocity of fluid inside tube, lb/hr·ft^2,
g_c = gravitational conversion constant, lb$_m$·ft/lb$_f$·hr^2, and
ρ = density of fluid inside tube, lb/ft^3.

The friction factor is given by the expression[4]

$$f = 0.00140 + 0.125\left(\frac{\mu_i}{d_i G}\right)^{0.32} . \tag{4.18}$$

The pressure drops on the shell side of the steam generator exchanger are calculated by using the equations recommended by Bergelin.[4] The pressure drop across the i-th cross-flow region is given by the expression

$$\Delta P_{Bi} = \frac{0.6r_B}{144}\left(\frac{G_B^2}{2g_c\rho}\right) , \tag{4.19}$$

where

r_B = number of restrictions in cross-flow region,
G_B = mass velocity of fluid in cross-flow region, lb/hr·ft^2, and
ρ = density of fluid, lb/ft^3.

The pressure drop across the i-th baffle window is given by the expression

$$\Delta P_{w_i} = \frac{(2 + 0.6r_w)}{144}\left(\frac{G_m^2}{2g_c\rho}\right) , \tag{4.20}$$

where

r_w = number of restrictions in window region and

G_m = mean mass velocity (given by Eq. 4.7), lb/hr·ft^2.

The total pressure drop on the shell side of the exchanger is given by the expression

$$\Delta P_s = B_p\left(\sum_{i=1}^{N+1} \Delta P_{B_i} + \sum_{i=1}^{N} \Delta P_{w_i}\right) , \tag{4.21}$$

where

B_p = bypass leakage correction factor for pressure recommended by Bergelin[4] and

N = number of baffles.

Detailed stress calculations are not included in the SUPEX computer program, but an approximate value of the allowable temperature drop across the tube wall based on thermal stress considerations is determined for each increment of tube length. This value of allowable temperature drop can be compared with the value of the temperature drop across the tube wall determined in the heat transfer calculations to provide some guidance in selecting design parameters. The thermal stresses are treated as secondary stresses. Based on the requirements set forth in Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code; the permissible value for the thermal stresses is given by the expression

$$\Delta T^{\sigma}{}_h = \Delta T^{\sigma}{}_L = 3S_m - S , \tag{4.22}$$

where

$\Delta T^{\sigma}{}_h$, $\Delta T^{\sigma}{}_L$ = hoop and longitudinal stress components caused by temperature differences across the tube wall, psi,

S_m = allowable stress intensity based on rules prescribed in Section III of the ASME Boiler and Pressure Vessel Code, psi, and

S = total stress intensity resulting from primary membrane stresses plus secondary stresses from all sources other than thermal stresses, psi.

The value of S was conservatively estimated to be about 26,000 psi. The tube wall material is Hastelloy N, and

$$\text{for } T_W < 1015°\text{F}, \quad S_m = 24{,}000 - 7.5(T_W) \tag{4.23}$$

and

$$\text{for } 1015°\text{F} \leq T_W \leq 1100°\text{F}, \quad S_m = 57{,}000 - 40(T_W) \ . \tag{4.24}$$

Based on data reported by J. F. Harvey,[15] the hoop and longitudinal stresses resulting from temperature differences across the tube wall are given by the expression

$$\Delta T^{\sigma}h = \Delta T^{\sigma}L = \frac{-\alpha E(\Delta T_W)}{2(1 - \nu)\left(\ln \dfrac{d_o}{d_i}\right)}\left[1 - \frac{2d_o^2}{d_o^2 - d_i^2}\left(\ln \frac{d_o}{d_i}\right)\right] \ , \tag{4.25}$$

where

α = coefficient of thermal expansion, in./in.·°F,

E = modulus of elasticity for Hastelloy N, psi,

ΔT_W = temperature drop across tube wall, °F,

ν = Poisson's ratio,

d_o = outside diameter of tube, in., and

d_i = inside diameter of tube, in.

The estimated value of S and Eqs. 4.22, 4.23, 4.24, and 4.25 are used in the SUPEX computer program to calculate the allowable value of ΔT_W. The values of E and α are determined in the computer program from Eqs. 4.26 and 4.27.

$$E = [31.65 - 0.005(T_W)] \times 10^6 \tag{4.26}$$

and

$$\alpha = [0.0031(T_W) + 5.91] \times 10^{-6} \ . \tag{4.27}$$

Although detailed stress calculations are not included in the SUPEX computer program, a preliminary stress analysis of the steam generator exchanger was made by hand. This preliminary analysis was based on the requirements of Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code; and the hand calculated values are compared with allowable values in Table 4.2. The allowable stress values were taken from data in code case interpretations 1315-3 (Ref. 16) and 1331-4 (Ref. 17).

Table 4.2. Preliminary Stress Calculations for MSBR Steam Generator

Maximum stress intensity,[a] psi	
Tube	
Calculated	P_m = 13,900; $(P_m + Q)$ = 30,900
Allowable[b]	P_m = 15,500; $(P_m + Q)$ = 46,500
Shell	
Calculated	P_m = 5800; $(P_m + Q)$ = 13,200
Allowable[c]	P_m = 8800; $(P_m + Q)$ = 26,400
Maximum tube sheet stress, psi	
Calculated	<17,000
Allowable[d]	17,000

[a] The symbols are those of Section III of the ASME Boiler and Pressure Vessel Code where

P_m = primary membrane stress intensity, psi,

Q = secondary stress intensity, psi,

S_m = allowable stress intensity, psi.

[b] Based on a temperature of 1038°F for the inside surface of the tubes; this represents the worst stress condition.

[c] Based on the maximum or highest temperature of the coolant salt of 1150°F.

[d] Based on a temperature of 1000°F for the steam and use of a baffle on the shell side.

4.3 Description of SUPEX

The equations described in Subsection 4.2 are used in the SUPEX program to size the steam generator exchanger for the specified input data. A flow diagram of the SUPEX program, a list of the input required, and a list of the output received from the computer are given in Appendix D.

In the SUPEX program, the total heat to be transferred in the exchanger is divided into a specified number of equal increments. For each increment, heat balance relations for the coolant salt and the supercritical fluid and the heat transfer equations are used to determine the change of temperature for each stream and the tube length required. The pressure drop in the supercritical fluid for each increment and the pressure drop in the coolant salt for each baffle space are calulated and summed.

Two major iteration loops are contained in the SUPEX program. First, the baffle spacing is assumed and iterations are made until the total calculated shell-side pressure drop agrees with that specified. Internal to this loop, the number of tubes in the exchanger is estimated, and iterations are made to give the total tube-side pressure drop specified. A simplified flow diagram of the SUPEX program, a complete listing of the program, and a list of terms used in the program are given in Appendix D.

Output from the program includes the number of tubes, inside diameter of the shell, length of the exchanger, baffle spacing, number of baffles, total heat transfer area, and the apparent overall heat transfer coefficient. The method of calculation used in the program permits the total length of the tubes to differ from the total length of the baffle space by a fraction of the baffle spacing. Both lengths are given in the output, as are the heat transfer area and apparent heat transfer coefficient for each length. The output also includes pertinent information for each baffle spacing and tube increment.

To illustrate the use of the SUPEX program, the computer input data for the MSBR steam generator superheater exchanger described in Subsection 4.1 and the output data printed by the computer are included in Appendix D. The time required for a typical IBM 360/91 computer run of this program is about 30 seconds.

4.4 Evaluation of SUPEX

The problem of stability in the steam generator superheater was considered. As indicated by K. Goldman et al.[18] and by L. S. Tong,[19] instabilities in steam generators can arise from two sources. First, a true thermodynamic instability can exist where, for a given pressure drop across the tube, the flow rate through the tube may be changed from one steady-state value to another by a finite disturbance. Second, a system instability that is caused by resonant conditions in the fluid can exist. Data related to the first type of instability have been reported by L. Y. Krasyakova and B. N. Glusker,[20] and data related to the second type of instability have been reported by E. R. Quandt[21] and by L. M. Shotkin.[22] A qualitative evaluation of these data indicates that the mass flow rate, pressure drop, and heat flux used in the horizontal U-tube and U-shell design will result in stable operation. Operation of a test module will provide further information about the stability of this design concept.

An analysis was made to evaluate the various uncertainties involved in the SUPEX computer program. Tolerances were placed on the physical properties of the coolant salt, the heat transfer coefficients, and on the pressure-drop correlation. The program was run for various cases to determine the quantitative values of the favorable and the adverse effects of the uncertainties. The favorable effects were defined as decreased heat transfer area, decreased shell diameter, and decreased total tube length. The adverse effects were defined as increased values for these same three parameters. The selection of these parameters was based on the belief that the heat transfer area is indicative of the total cost of the exchanger, the diameter of the shell is indicative of the stress problem, and the total length of the tubes is indicative of the physical size of the exchanger.

The range of uncertainties studied included the physical properties of the coolant salt with a deviation of ±2% for the specific heat and density and a deviation of ±10% for the viscosity and thermal conductivity, the tube-side and shell-side heat transfer coefficients with a deviation of ± 20%, and the pressure-drop correlation with a deviation of ±10%.

Scrutiny of the shell-side heat transfer coefficient revealed that positive deviations (increases) in the specific heat and thermal conductivity of the coolant salt and negative deviations (decreases) in the density and viscosity of the salt will produce favorable effects, while opposite deviations will produce adverse effects. A negative deviation (decrease) in the calculated pressure drop will produce favorable effects, while a positive deviation (increase) will produce adverse effects.

The results of this analysis in terms of percentage changes relative to the design case are given in Table 4.3. Case 1 is for an increased specific heat and density of the coolant salt and a decreased viscosity and thermal conductivity. Case 2 is for deviations opposite to those of Case 1. Cases 3 and 4 are for increased and decreased, respectively, shell-side heat transfer coefficients; Cases 5 and 6 are for increased and decreased, respectively, tube-side heat transfer coefficients; and Cases 7 and 8 are for decreased and increased, respectively, calculated pressure drops. Case 9 for overall favorable conditions is for the combined effect of all favorable changes, and Case 10 for overall adverse conditions is for all adverse changes. Cases 1, 3, 5, and 7 represent favorable changes; while Cases 2, 4, 6, and 8 represent adverse changes.

Table 4.3. Percentage Deviations Resulting From Calculational Uncertainties Related to MSBR Steam Generator Exchanger

Case	Conditions	Heat Transfer Area	Shell Diameter	Total Tube Length
1	Favorable physical properties	-8.2	-1.4	-5.6
2	Adverse physical properties	+7.6	+1.2	+5.2
3	Increased shell-side heat transfer	-10.1	-1.6	-7.0
4	Decreased shell-side heat transfer	+13.5	+2.1	+8.8
5	Increased tube-side heat transfer	-2.3	-0.5	-1.3
6	Decreased tube-side heat transfer	+4.2	+0.9	+2.3
7	Decreased calculated pressure drop	-2.6	-0.5	-1.6
8	Increased calculated pressure drop	+1.8	+0.7	+0.5
9	Overall favorable	-21	-4	-15
10	Overall adverse	+30	+5	+18

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APPENDICES

Appendix A

PHYSICAL PROPERTY DATA

The design properties of the fuel salt used in the concept of a single-fluid MSBR and incorporated in the PRIMEX computer program are given in Table A.1. The design properties of the coolant salt used in the MSBR concept and incorporated in the PRIMEX, RETEX, and SUPEX computer programs are given in Table A.2; and the design properties of Hastelloy N used in the MSBR concept and incorporated in these computer programs are given in Table A.3.

Values for the density, viscosity, and thermal conductivity of the fuel and coolant salts were taken from data reported in Ref. A.1. The value given for the heat capacity of the fuel salt is taken from Ref. A.2, and the value given for the heat capacity of the coolant salt is taken from Ref. A.3. These references are listed below.

A.1. Oak Ridge National Laboratory, "Molten-Salt Reactor Program Semiannual Progress Report August 31, 1969," USAEC Report ORNL-4449, February 1970.

A.2. Oak Ridge National Laboratory, "Molten-Salt Reactor Program Semiannual Progress Report August 31, 1968," USAEC Report ORNL-4344, February 1969.

A.3. Oak Ridge National Laboratory, "Molten-Salt Reactor Program Semiannual Progress Report February 29, 1969," USAEC Report ORNL-4254, August 1969.

Table A.1. Design Properties of MSBR Fuel Salt

Fuel salt components	$^7LiF\text{-}BeF_2\text{-}ThF_4\text{-}UF_4$
Composition, mole %	71.7-16-12-0.3
Approximate molecular weight	64
Approximate melting point, °F	930
Vapor pressure at 1150°F, mm Hg	<0.1
Density,[a]	
g/cm³	$\rho = 3.752 - (6.68 \times 10^{-4})T°C$
lb/ft³	$\rho = 235.0 - 0.02317T°F$
At 1300°F	$\rho = 204.9$ lb/ft³
At 1175°F	$\rho = 207.8$ lb/ft³
At 1050°F	$\rho = 210.7$ lb/ft³
Viscosity,[b]	
Centipoise	$\mu = 0.109\left(\exp \frac{4090}{T°K}\right)$
lb/ft·hr	$\mu = 0.2637\left(\exp \frac{7362}{T°R}\right)$
At 1300°F	$\mu = 17.29$ lb/ft·hr
At 1175°F	$\mu = 23.78$ lb/ft·hr
At 1050°F	$\mu = 34.54$ lb/hr·ft
Heat capacity,[c]	$C_p = 0.324$ Btu/lb·°F ± 4%
Thermal conductivity[d]	
At 1300°F	$k = 0.69$ Btu/hr·°F·ft
At 1175°F	$k = 0.71$ Btu/hr·°F·ft
At 1050°F	$k = 0.69$ Btu/hr·°F·ft

[a] Figure 13.6 on page 147 of Ref A.1.

[b] Table 13.2 on page 145 of Ref A.1.

[c] Page 163 of Ref. A.2.

[d] Figure 9.13 on page 92 of Ref. A.1. The value of k shown is for salt with about 5% less LiF than in the reference salt. Addition of LiF would increase the average value to about 0.72 to 0.74. The established and conservative value of 0.71 was used in the calculations for the MSBR concept.

Table A.2. Design Properties of MSBR Coolant Salt

Coolant salt components	$NaBF_4$-NaF
Composition, mole %	92-8
Approximate molecular weight	104
Approximate melting point, °F	725
Vapor pressure at 1150°F, mm Hg	252
Density,[a]	
g/cm³	$\rho = 2.252 - (7.11 \times 10^{-4})T°C$
lb/ft³	$\rho = 141.4 - 0.0247T°F$
At 1150°F	$\rho = 113.0$ lb/ft³
At 1000°F	$\rho = 116.7$ lb/ft³
At 850°F	$\rho = 120.4$ lb/ft³
Viscosity,[b]	
Centipoise	$\mu = 0.0877\left(\exp \frac{2240}{T°K}\right)$
lb/ft·hr	$\mu = 0.2121\left(\exp \frac{4032}{T°R}\right)$
At 1150°F	$\mu = 2.60$ lb/ft·hr
At 1000°F	$\mu = 3.36$ lb/ft·hr
At 850°F	$\mu = 4.61$ lb/ft·hr
Heat capacity[c]	$C_p = 0.360$ Btu/lb·°F ± 2%
Thermal conductivity,[d]	
At 1150°F	k = 0.23 Btu/hr·°F·ft
At 1000°F	k = 0.23 Btu/hr·°F·ft
At 850°F	k = 0.26 Btu/hr·°F·ft

[a] Figure 13.6 on page 147 of Ref. A.1.

[b] Table 13.2 on page 145 of Ref. A.1.

[c] Page 168 of Ref. A.3.

[d] Figure 9.13 on page 92 of Ref. A.1.

Table A.3. Design Properties of Hastelloy N

Composition, wt %	
Nickel	Balance
Molybdenum	12
Chromium	7
Iron	0 to 4
Manganese	0.2 to 0.5
Silicon, maximum	0.1
Boron, maximum	0.001
Titanium	0.5 to 1.0
Hafnium or niobium	0 to 2
Cu, Co, P, S, C, W, Al	0.35
Density, lb/ft^3	
At 80°F	557
At 1300°F	541
Thermal conductivity, Btu/hr·ft·°F	
At 80°F	6.0
At 1300°F	12.6
Specific heat, Btu/lb·°F	
At 80°F	0.098
At 1300°F	0.136
Thermal expansion per °F	
At 80°F	5.7×10^{-6}
At 1300°F	9.5×10^{-6}
Modulus of elasticity, psi	
At 80°F	31×10^{6}
At 1300°F	25×10^{6}
Tensile strength, psi	
At 80°F	~115,000
At 1300°F	~75,000
Maximum allowable design stress at 1300°F, psi	
At 80°F	25,000
At 1300°F	3500
Melting temperature, °F	2500

Appendix B

THE PRIMEX PROGRAM

The PRIMEX computer program is outlined in block-diagram form in Fig. B.1. The input data required for the program are given in Table B.1, and the output received from the program are given in Table B.2. A complete listing of the main program and its two subroutines is followed by definitions of the intermediate variables used in the program. To illustrate the use of the PRIMEX program, the input and output for the MSBR primary heat exchanger discussed in Subsection 2.1 of this report are presented as printed by the computer.

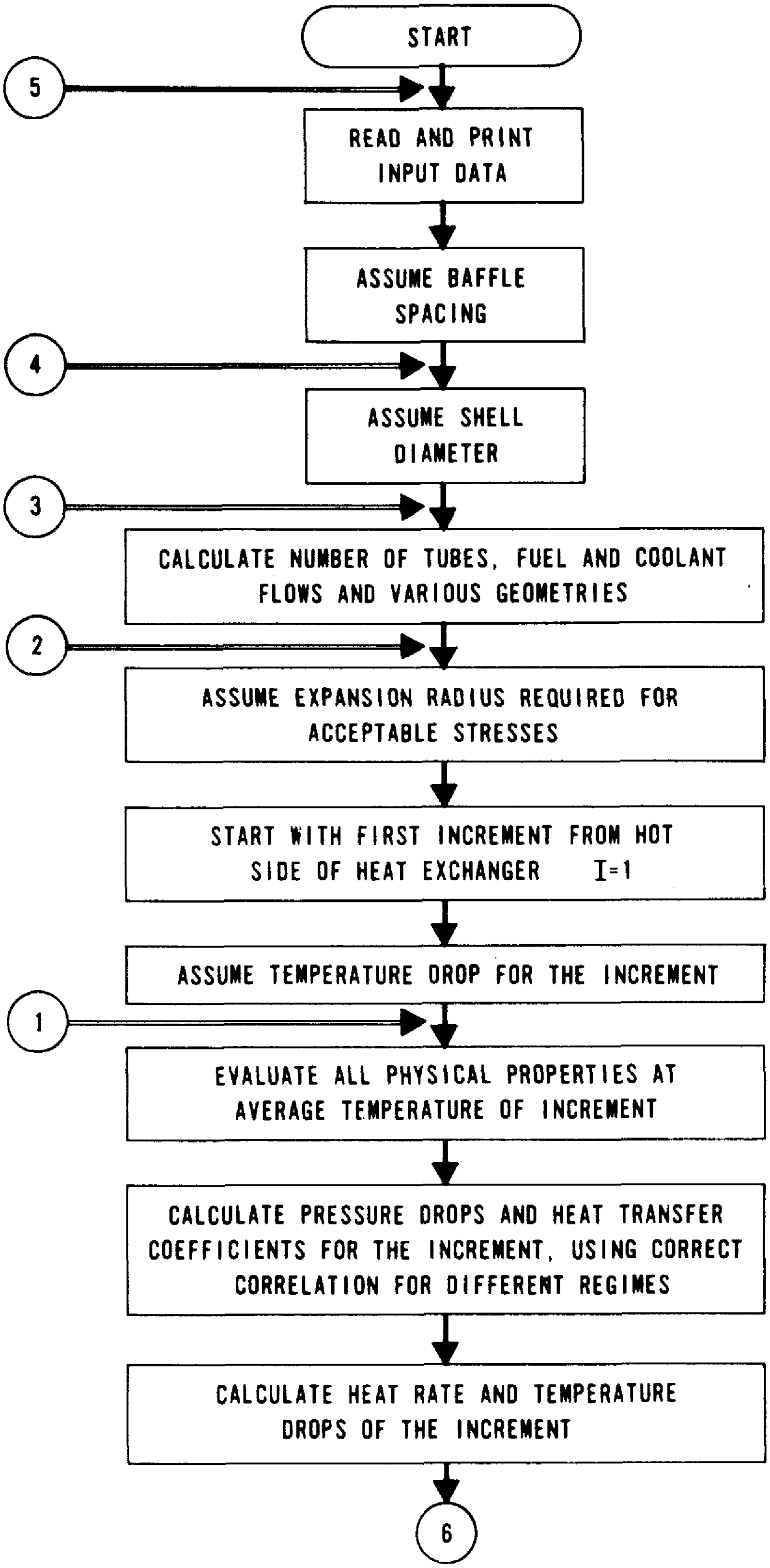

Fig. B.1. Simplified Flow Diagram of the PRIMEX Computer Program.

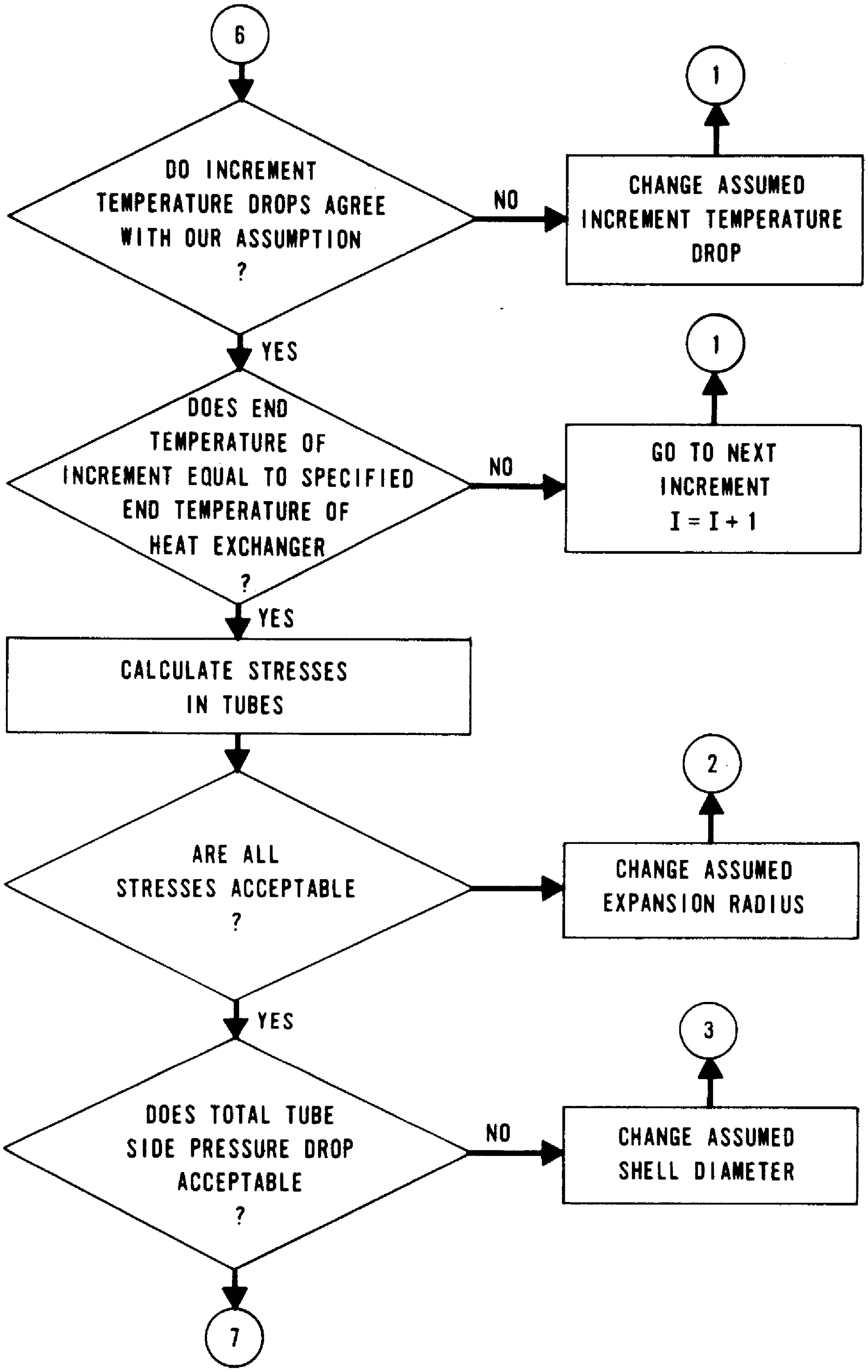

Fig. B.1. (continued)

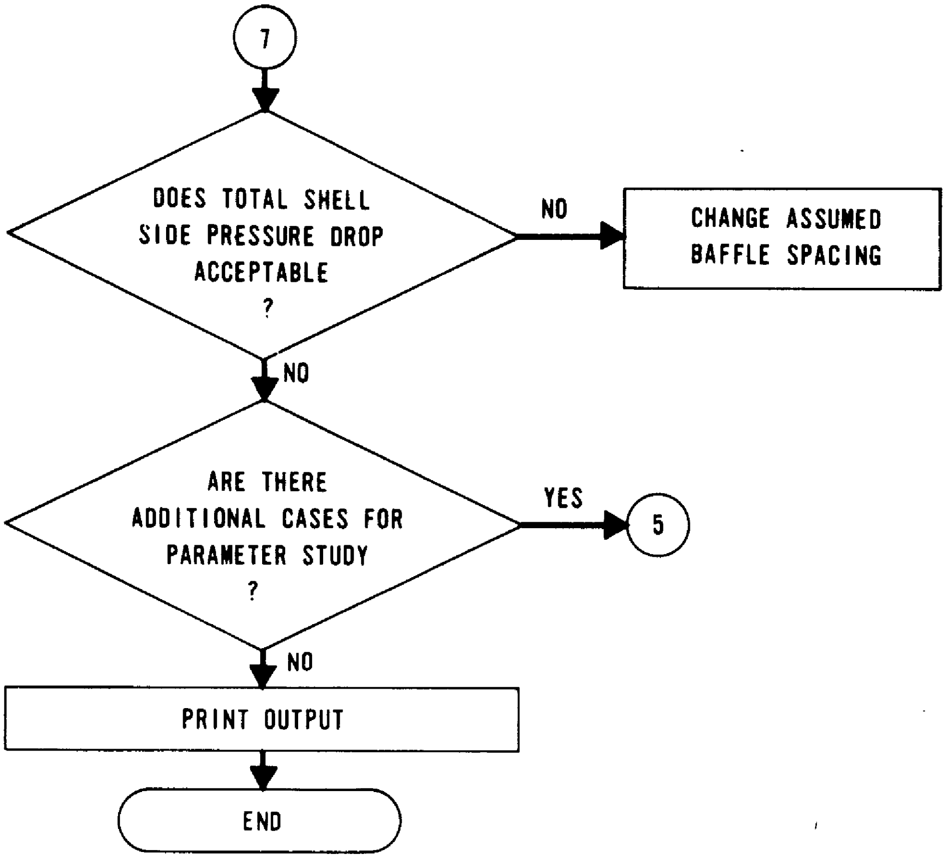

Fig. B.1. (continued)

Table B.1. Computer Input Data for PRIMEX Program

Card	Columns	Format	Variable	Term	Units
A	1-10	E10.4	Heat load required	HEATL	Btu/hr
	11-20	F10.0	Allowable tube-side pressure drop	PRDT	lb/ft^2
	21-30	F10.0	Allowable shell-side pressure drop	PRDS	lb/ft^2
	31-40	F10.0	Tube-side inlet pressure	TPIN	lb/ft^2
	41-50	F10.0	Shell-side outlet pressure	SPOUT	lb/ft^2
B	1-10	F10.0	Coolant outlet temperature	CTO	°F
	11-20	F10.0	Fuel inlet temperature	FTO	°F
	21-30	F10.0	Fuel outlet temperature	ETF	°F
	31-40	F10.0	Coolant inlet temperature	ETC	°F
C	1-10	F10.0	Leakage factor for heat transfer correlations	LK	
	11-20	F10.0	Leakage factor for pressure drop calculations	PLK	
	21-30	F10.0	Tube material conductivity	WCOND	Btu/hr•ft•°F
	31-40	F10.0	Arc of bent tube for thermal expansion	ARC	Degrees
	41-45	I5	Number of pair points in Stress intensity table for tube material	ICNPT	
D_1, D_2 .	1-10	F10.0	Stress intensity at CTM temperature	CASM	psi
D_{ICNPT}	11-20	F10.0	Temperature	CTM	°F
E	1-10	F10.0	Radius of coolant central downcomer	RA5	ft
	11-20	F10.0	Distance between shell wall and tube bundle	DTR	ft
	21-30	F10.0	Maximum anticipated heat exchanger radius	RASMAX	ft
	31-35	I5	Number of cases to be run	KASES	
	36-40	I5	Index one if enhanced tubes are used	KENTB	
	41-45	I5	Index one if stress analysis is included	KTBST	
F_1, F_2 .	1-10	F10.0	Outside diameter of tubes	DIA	ft
...	11-20	F10.0	Tube wall thickness	WTHK	ft
F_{KASES}	21-30	F10.0	Radial pitch	RPI	ft
	31-40	F10.0	Circumferential pitch	BCPI	ft
	41-50	F10.0	Inner baffle cut	CUT3	% of area
	51-60	F10.0	Outer baffle cut	CUT4	% of area

Table B.2. Output Data From PRIMEX Computer Program

Term	Variable	Units
THEATO	Total heat actually transferred	Btu/hr
HTPERC	Percentage of required heat load actually transferred	
QC	Coolant (shell-side) mass flow rate	lb/hr
QF	Fuel (tube-side) mass flow rate	lb/hr
TTDSO	Total tube-side pressure drop	psi
SPPERC	Percentage of allowed tube pressure drop actually used	
TTDTU	Total shell-side pressure drop	psi
TPPERC	Percentage of allowed shell pressure drop actually used	
RA8	Radius of heat exchanger shell	ft
BSOI	Distance between baffles	ft
VOL	Fluid volume contained in tubes	ft^3
AREA	Total heat transfer area in heat exchanger	ft^2
SNT	Total number of tubes	
TUBLEN	Actual tube length	ft
HEXLEN	Heat exchanger length from lower tube sheet to upper nozzle of tubes	ft
STRLEN	Straight section length of tubes	ft
EXPRAD	Radius of tube bends for thermal expansion	ft
BRL1	Modification factor for Bergelin's heat transfer correlation	
PSTO	Primary stresses on outer surface of tubes	psi
PQSTO	Combined primary and secondary stresses on outer surface of tubes	psi
PQFSTO	Combined primary, secondary, and peak stresses on outer surface of tubes	psi
PSTI	Primary stresses on inner surface of tubes	psi
PQSTI	Combined primary and secondary stresses on inner surface of tubes	psi
PQFSTI	Combined primary, secondary, and peak stresses on inner surface of tubes	psi
SAVT	Shell average temperature	°F
TAVT	Tube average temperature	°F

Table B.2 (continued)

Term	Variable	Units
TCI(I)	Coolant outlet temperature from increment I	°F
TCO(I)	Coolant inlet temperature from increment I	°F
CWT(I)	Average tube wall temperature at coolant side	°F
TFI(I)	Fuel outlet temperature from increment I	°F
TFO(I)	Fuel inlet temperature from increment I	°F
FWT(I)	Average tube wall temperature at fuel side	°F
TWDT(I)	Average temperature drop across tube wall in increment I	°F
VM1(I)	Fluid average velocity in outer window in increment I	ft/sec
VM2(I)	Fluid average velocity in overlapping baffle zone in increment I	ft/sec
VM3(I)	Fluid average velocity in inner window in increment I	ft/sec
VWO1(I)	Fluid velocity across tubes in outer edge of baffle in increment I	ft/sec
VWO3(I)	Fluid velocity across tubes in inner edge of baffle in increment I	ft/sec
PDSO(I)	Shell-side pressure drop for increment I	lb/ft^2
PDTO(I)	Tube-side pressure drop for increment I	lb/ft^2
RENTO(I)	Tube-side Reynolds number for increment I	
PRNTO(I)	Tube-side Prandtl number for increment I	
RENSO1(I)	Reynolds number in outer window increment I	
RENSO2(I)	Reynolds number in overlapping baffle zone in increment I	
RENSO3(I)	Reynolds number in inner window in increment I	
HTO(I)	Tube-side heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
AHSO(I)	Shell-side heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
UOA(I)	Overall heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
HEAT(I)	Heat transferred in increment I	Btu/hr

The PRIMEX Program Listing

```
**FTN,L,E,G,M.
      PROGRAM MSBRPE-2                                                  MSBRP  10
      TYPE REAL     LK ,LAW01 , LAW03                                   MSBRP  20
      DIMENSION TFO( 75),TCI(75),VM1(75),VM2(75),VWC1(75),VWC3(75),     MSBRP  30
     1RENTO( 75),PRNTO( 75),RENSO1(75),RENSO2(75),RENSO3(75),           MSBRP  31
     2VM3(75),PDSO(75),NT(100),BJ(3),HS01(75),HSC2(75),HS03(75),        MSBRP  32
     3AHSO(75),HTO(75),UOA(75),TCO(75),TFI(75),HEAT(75),TWDT(75),       MSBRP  33
     4PDTO(75), TUBLN(75),     V1(75),V2(75),V3(75),VW1(75),VW3(75),    MSBRP  34
     5 R(100),FACT(100),TCPI(100),TOTAL(100),CASM(6) ,CTM(6)            MSBRP  35
     6  CWT(75),FWT( 75),AVWT(75)                                       MSBRP  36
 1001 FORMAT( E10.4, 4F10.0)                                            MSBRP  40
 1002 FORMAT( 4F10.0)                                                   MSBRP  50
 1003 FORMAT( 4F10.0,I5)                                                MSBRP  60
 1004 FORMAT(2F10.4)                                                    MSBRP  70
 1005 FORMAT( 3F10.0,3I5)                                               MSBRP  80
 1006 FORMAT( 6F10.0)                                                   MSBRP  90
 1007 FORMAT (1H1,7X,1HI,8X,3HCTM,7X,4HCASM//(4X,I5,2F12.2))            MSBR  100
 1008 FORMAT(22HOHEAT LOAD REQUIRED = ,F12.0,2X,8H(BTU/HR))             MSBR  110
 1009 FORMAT(43HOALLOWABLE TOTAL TUBE-SIDE PRESSURE DRCP = ,F10.0,2X,   MSBR  120
     1  10H(LB/SQ-FT) )                                                 MSBR  121
 1010 FORMAT(44HCALLOWABLE TCTAL SHELL-SIDE PRESSURE CROP = ,F10.0,2X,  MSBR  130
     1  10H(LB/SQ-FT) )                                                 MSBR  131
 1011 FORMAT(23HOTUBE INLET PRESSURE = ,F10.0,2X,1CH(LB/SQ-FT))         MSBR  140
 1012 FORMAT(24HOSHELL OUTLET PRESSURE =,F10.0,2X,10H(LB/SQ-FT))        MSBR  150
 1013 FORMAT(33HOHIGH TEMP. OF SHELL SIDE FLUID =,F10.2,2X,3H(F))       MSBR  160
 1014 FORMAT(33HOHIGH TEMP. OF TUBE SIDE FLUID =  ,F10.2,2X,3H(F))      MSBR  170
 1015 FORMAT(32HOLOW TEMP. OF TUBE SIDE FLUID =  ,F10.2,2X,3H(F))       MSBR  180
 1016 FORMAT(32HOLOW TEMP. OF SHELL SIDE FLUID =,F1C.2,2X,3H(F))        MSBR  190
 1017 FORMAT(32HOHEAT TRANSFER LEAKAGE FACTOR = ,F10.5)                 MSBR  200
 1018 FORMAT(27HOPRESSURE LEAKAGE FACTOR = ,F10.5 )                     MSBR  210
 1019 FORMAT(35HOCONDUCTIVITY OF TUBE WALL METAL = ,F1C.5,2X,           MSBR  220
     1  13H(BTU/HR-FT-F) )                                              MSBR  221
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1020 FORMAT(37H0ARC OF FOUR BENDS FOR FLEXIBILITY = ,F10.2,2X,         MSBR 230
    1  9H(DEGREES))                                                     MSBR 231
1021 FORMAT(34H0INSIDE RADIUS OF OUTER ANNULUS = ,F10.5,2X,6H(FEET))    MSBR 240
1022 FORMAT(41H0DISTANCE BETWEEN SHELL WALL AND TUBES =                 MSBR 250
    1 ,F10.5,2X,6H(FEET))                                               MSBR 251
1023 FORMAT(49H0MAXIMUM ANTICIPATED OUTER RADIUS OF EXCHANGER = ,       MSBR 260
    1      F10.5,2X,6H(FEET) )                                          MSBR 261
1024 FORMAT(23H0NUMBER OF CASES RUN = ,I4)                              MSBR 270
1025 FORMAT(25H0USE OF ENHANCED TUBES = ,I4,2X,32H(ONE IF ENHANCED TUBEMSBR 280
    1S ARE USED))                                                       MSBR 281
1026 FORMAT(1H0,36HUSE OF STRESS ANALYSIS SUBROUTINE = ,                MSBR 290
    1   I4,2X,19H(ONE IF TO BE USED))                                   MSBR 291
1027 FORMAT(29H0OUTSIDE DIAMETER OF TUBES = ,F10.5,2X,  6H(FEET) )      MSBR 300
1028 FORMAT(27H0WALL THICKNESS OF TUBES = ,F10.5,2X,  6H(FEET) )        MSBR 310
1029 FORMAT(16H0RADIAL PITCH = ,F10.5,2X,  6H(FEET))                    MSBR 320
1030 FORMAT(25H0CIRCUMFERENTIAL PITCH = ,F10.5,2X,  6H(FEET))           MSBR 330
1031 FORMAT(22H0INNER BAFFLE CUT3  = ,F10.5,2X, 10H(PER CENT) )         MSBR 340
1032 FORMAT(22H0OUTER BAFFLE CUT4  = ,F10.5,2X, 10H(PER CENT) )         MSBR 350
1033 FORMAT(25H1TOTAL HEAT TRANSFERED = ,F12.0,2X,8H(BTU/HR),           MSBR 360
    1      2X,1H(,F5.1,9H PERCENT))                                     MSBR 361
1034 FORMAT(29H0MASS FLOW RATE OF COOLANT = ,F10.0,2X, 7H(LB/HR) )      MSBR 370
1035 FORMAT(26H0MASS FLOW RATE OF FUEL = ,F10.0,2X, 7H(LB/HR) )         MSBR 380
1036 FORMAT(34H0SHELL-SIDE TOTAL PRESSURE DROP = ,F10.2,2X, 9H(LB/SQIN)MSBR 390
    1      ,2X,1H(,F5.1,9H PERCENT))                                    MSBR 391
1037 FORMAT(33H0TUBE-SIDE TOTAL PRESSURE DROP = ,F10.2,2X, 9H(LB/SQIN),MSBR 400
    1      2X,1H(,F5.1,9H PERCENT))                                     MSBR 401
1038 FORMAT(24H0NOMINAL SHELL RADIUS = ,F7.4,2X,4H(FT))                 MSBR 410
1039 FORMAT(26H0UNIFORM BAFFLE SPACING = ,F7.4,2X,4H(FT))               MSBR 420
1040 FORMAT(40H0TUBE FLUID VOLUME CONTAINED IN TUBES = ,F7.2,1X,        MSBR 430
    112H(CUBIC FEET))                                                   MSBR 431
1041 FORMAT(1H0,46HTOTAL HEAT TRANSFER AREA BASED ON TUBE O.D. = ,      MSBR 440
    1   F12.2,2X,6H(SQFT))                                              MSBR 441
1042 FORMAT(25H0TOTAL NUMBER OF TUBES = ,F6.0)                          MSBR 450
1043 FORMAT(21H0TOTAL TUBE LENGTH = ,F6.2,2X,4H(FT))                    MSBR 460
1044 FORMAT(29H0HEAT EXCH. APPROX. LENGTH = ,F6.2,2X,6H(FEET))          MSBR 470
1045 FORMAT(35H0STRAIGHT SECTION OF TUBE LENGTH = ,F6.2,2X,4H(FT))      MSBR 480
1046 FORMAT(38H0RADIUS OF THERMAL EXPANSION CURVES = ,F6.2,2X,6H(FEET))MSBR 490
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 1047 FORMAT(31HOBERGLIN MODIFICATION FACTOR = ,F5.2)                   MSBR 500
 1048 FORMAT(1HO,2X,1HI,7X,3HTCI,9X,3HTCO,9X,3HCWT,9X, 3HTFI,9X,3HTFO,  MSBR 510
     19X,3HFWT,8X,4HTWDT//11X,1HF,11X,1HF,11X,1HF,11X,                  MSBR 511
     2      1HF,11X,1HF,11X,1HF,11X,1HF//(1X,I3,7E12.4))                MSBR 512
 1049 FORMAT(1HO,2X,1HI,9X,2HV1, 9X,2HV2 ,9X,2HV3 ,9X,3HVW1 ,9X,3HVW3 , MSBR 520
     1 8X,4HPDSO,8X,4HPDTO//32X,6HFT/SEC,33X,7HLB/SQFT//(1X,I3,7F12.4)) MSBR 521
 1050 FORMAT(1HO,2X,1HI,5X,5HRENTO,7X,5HPRNTO,7X,6HRENSO1,6X,6HRENSO2,  MSBR 530
     16X,6HRENSO3,7X,3HHTO,8X,4HAHSO,9X,3HUOA,8X,4HHEAT//77X,           MSBR 531
     2  13HBTU/HR/SQFT/F,13X,6HBTU/HR//(1X,I3,9E12.4))                  MSBR 532
 1051 FORMAT(27HOTUBE WALL AVERAGE TEMP. =  ,F10.2)                     MSBR 540
 1052 FORMAT(28HOSHELL SIDE AVERAGE TEMP. =  , F10.2)                   MSBR 550
 1053 FORMAT(1HO,34HP STRESS AT TUBE OD AND TUBE ID = ,     2F10.2,1X,  MSBR 560
     1 9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,3H   ))                 MSBR 561
 1054 FORMAT(1HO,36HP+Q STRESS AT TUBE OD AND TUBE ID = ,               MSBR 570
     1           2F10.2,1X,9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,    MSBR 571
     2 3H   ))                                                          MSBR 572
 1055 FORMAT(1HO,38HP+Q+F STRESS AT TUBE OD AND TUBE ID = ,             MSBR 580
     1           2F10.2,1X,9H(LB/SQIN)//18H(SHOULD NOT EXCEED,F10.2,    MSBR 581
     2 3H   ))                                                          MSBR 582
C                                                                       MSBR 650
C     READ IN AND PRINT OUT INPUT DATA                                  MSBR 660
      KEY7= 1                                                           MSBR 610
      VM1(1)=0.                                                         MSBR 620
      VM2(1)=0.                                                         MSBR 630
      VM3(1)=0.                                                         MSBR 640
      VWO1(1)=0.                                                        MSBR 650
      VWO3(1)=0.                                                        MSBR 660
      RENSO1(1)=0.                                                      MSBR 670
      RENSO2(1)=0.                                                      MSBR 680
      RENSO3(1)=0.                                                      MSBR 690
      HSO1(1)=0.                                                        MSBR 700
      HSO2(1)=0.                                                        MSBR 710
      HSO3(1)=0.                                                        MSBR 720
      HEFI = 1.                                                         MSBR 730
      HEFO = 1.                                                         MSBR 740
C                                                                       MSBR 810
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      READ 1001, HEATL, PRDT, PRDS ,TPIN,SPOUT                          MSBR 760
      READ 1002, CTO, FTO, ETF, ETC                                     MSBR 770
      READ 1003, LK, PLK,WCOND,ARC,ICNPT                                MSBR 780
      READ 1004,(CASM(K),CTM(K),K=1,ICNPT)                              MSBR 790
      READ 1005, RA5, DTR, RA8MAX,KASES,KENTB,KTBST                     MSBR 800
    1 CONTINUE                                                          MSBR 810
      READ 1006, DIA, WTHK, RPI, BCPI, CUT3, CUT4                       MSBR 820
      HSFCT=1.
      IF(FTO.LT.CTO) HSFCT=-1.
      PRINT 1007,(K,CTM(K),CASM(K),K=1,ICNPT)                           MSBR 830
      PRINT 1008, HEATL                                                 MSBR 840
      PRINT 1009, PRDT                                                  MSBR 850
      PRINT 1010, PRDS                                                  MSBR 860
      PRINT 1011, TPIN                                                  MSBR 870
      PRINT 1012, SPOUT                                                 MSBR 880
      PRINT 1013, CTO                                                   MSBR 890
      PRINT 1014, FTO                                                   MSBR 900
      PRINT 1015, ETF                                                   MSBR 910
      PRINT 1016, ETC                                                   MSBR 920
      PRINT 1017, LK                                                    MSBR 930
      PRINT 1018, PLK                                                   MSBR 940
      PRINT 1019, WCOND                                                 MSBR 950
      PRINT 1020, ARC                                                   MSBR 960
      PRINT 1021, RA5                                                   MSBR 970
      PRINT 1022, DTR                                                   MSBR 980
      PRINT 1023, RA8MAX                                                MSBR 990
      PRINT 1024 , KASES                                                MSB 1000
      PRINT 1025, KENTB                                                 MSB 1010
      PRINT 1026, KTBST                                                 MSB 1020
      PRINT 1027, DIA                                                   MSB 1030
      PRINT 1028, WTHK                                                  MSB 1040
      PRINT 1029, RPI                                                   MSB 1050
      PRINT 1030, BCPI                                                  MSB 1060
      PRINT 1031, CUT3                                                  MSB 1070
      PRINT 1032, CUT4                                                  MSB 1080
C                                                                       MSB 1650
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C     BEGIN GEOMETRY CALCULATIONS FOR SINGLE ANNULUS COUNTER FLOW           MSB 1660
C     DISC AND DOUGHNUT BAFFLED HEAT EXCHANGER                              MSB 1670
      ARCR= 0.017452*ARC                                                    MSB 1120
      ATUBE =  (3.14159* (DIA**2.0))/4.0                                    MSB 1130
      GFTT = 1./3600.                                                       MSB 1140
      GFT = 1./144.                                                         MSB 1150
      DIAI=DIA-2.0*WTHK                                                     MSB 1160
      FATUB  =(3.14159*(DIAI**2.0))/4.0                                     MSB 1170
      KEY1 = 0                                                              MSB 1180
      PERC1 = 0.99                                                          MSB 1190
 2    IF(KEY1.GT.0)BSOI=0.5*(BSL+BSH)                                       MSB 1200
      KEY2 = 0                                                              MSB 1210
      PERC2 = 0.99                                                          MSB 1220
      RA8L=RA5                                                              MSB 1230
      RA8H=RA8MAX                                                           MSB 1240
 3    RA8=0.5*(RA8L  +RA8H  )                                               MSB 1250
      RJ8=(RA8-RA5-2.*DTR)/RPI+1.                                           MSB 1260
      IJ8=RJ8                                                               MSB 1270
      RIJ8=IJ8                                                              MSB 1280
      IF(RJ8-RIJ8-0.5)4,4,5                                                 MSB 1290
 4    J8=IJ8                                                                MSB 1300
      TRPI=(RA8-RA5-2.*DTR)/(RIJ8-1.)                                       MSB 1310
      CPI=BCPI*RPI/TRPI                                                     MSB 1320
      GO TO 6                                                               MSB 1330
 5    J8=IJ8+1                                                              MSB 1340
      TRPI=(RA8-RA5-2.*DTR)/RIJ8                                            MSB 1350
      CPI=BCPI*RPI/TRPI                                                     MSB 1360
 6    DO 7 I=1,J8                                                           MSB 1370
      R(I)=RA5+DTR+TRPI*(I-1)                                               MSB 1380
      FACT(I)=6.28318*R(I)                                                  MSB 1390
      NT(I)=FACT(I)/CPI                                                     MSB 1400
      TCPI(I)=FACT(I)/NT(I)                                                 MSB 1410
      IF(I.EQ.1)TOTAL(I)=NT(I)                                              MSB 1420
 7    IF(I.NE.1)TOTAL(I)=TOTAL(I-1)+NT(I)                                   MSB 1430
      NTO=TOTAL(J8)                                                         MSB 1440
      SNT=NTO                                                               MSB 1450
      RA52=RA5**2                                                           MSB 1460
      RA82=RA8**2                                                           MSB 1470
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      RA6=(RA52+CUT4*(RA82-RA52))**.5                                   MSB 1480
      J6=(RA6-R(1))/TRPI+1.                                             MSB 1490
      RA6=R(J6)+.5*TRPI                                                 MSB 1500
      RA7=(RA82-CUT3*(RA82-RA52))**.5                                   MSB 1510
      J7=(RA7-R(1))/TRPI+1.                                             MSB 1520
      RA7=R(J7)+.5*TRPI                                                 MSB 1530
      RA62=RA6**2                                                       MSB 1540
      RA72=RA7**2                                                       MSB 1550
      RB1=0.5*(J8-J7)                                                   MSB 1560
      RB2=J7-J6                                                         MSB 1570
      RB3=0.5*J6                                                        MSB 1580
      SUM1=TOTAL(J8)-TOTAL(J7)                                          MSB 1590
      SUM2=TOTAL(J7)-TOTAL(J6)                                          MSB 1600
      SUM3=TOTAL(J6)                                                    MSB 1610
      ISUM1=SUM1                                                        MSB 1620
      ISUM2=SUM2                                                        MSB 1630
      ISUM3=SUM3                                                        MSB 1640
      BSMAX=1.5*((RA8-(RA8-RA7)/2.)-(RA5+(RA6-RA5)/2.))                 MSB 1650
      BSMIN=0.2*(RA8-RA5)                                               MSB 1660
      IF(BSMIN.LT.0.1667)BSMIN=0.1667                                   MSB 1670
      APO1=3.14159*(RA82-RA72)-ATUBE*SUM1                               MSB 1680
      APO3=3.14159*(RA62-RA52)-ATUBE*SUM3                               MSB 1690
      LAWO1=6.28318*RA7-.5*DIA*(NT(J7)+NT(J7+1))                        MSB 1700
      LAWO3=6.28318*RA6-.5*DIA*(NT(J6)+NT(J6+1))                        MSB 1710
      HW=2.*WCOND/(DIA*(ALOG(DIA/DIAI)))                                MSB 1720
      CSPHAV=0.36                                                       MSB 1730
      FSPHAV=0.324                                                      MSB 1740
      QC=HEATL/(CSPHAV*(CTO-ETC))                                       MSB 1750
      QF=HEATL/(FSPHAV*(FTO-ETF))                                       MSB 1760
      GTO = QF/(NTO*FATUB)                                              MSB 1770
      KEY3=0                                                            MSB 1780
      XPRMAX=6.0                                                        MSB 1790
      XPRMIN= 0.                                                        MSB 1800
    8 EXPRAD= 0.5*(XPRMIN+XPRMAX)                                       MSB 1810
      IF(KTBST.EQ.0)EXPRAD=1.77                                         MSB 1820
      IF(KEY1.EQ.0)BSH=BSMAX                                            MSB 1830
      IF(KEY1.EQ.0)BSL=BSMIN                                            MSB 1840
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      IF(KEY1.EQ.0)BSOI=0.5*(BSL+BSH)                                   MSB 1850
      CURVES=0.069813*ARC*  EXPRAD+ 0.4*(RA8-RA5)+.25*BSOI              MSB 1860
      IT = 0                                                            MSB 1870
      KFINAL=0                                                          MSB 1880
9     I=1                                                               MSB 1890
      TSUM=0.                                                           MSB 1900
      SSUM=0.                                                           MSB 1910
      THEATO = 0.0                                                      MSB 1920
      TPDTO = 0.0                                                       MSB 1930
      TPDSO = 0.0                                                       MSB 1940
      TFO(I)=FTO                                                        MSB 1950
      TCI(I)=CTO                                                        MSB 1960
      TIF=-5.0                                                          MSB 1970
      TIC=-5.0                                                          MSB 1980
      CDTF=0.                                                           MSB 1990
      FDTF=0.                                                           MSB 2000
      BSO = BSOI                                                        MSB 2010
      BRL1 = BSO/((RA8-(RA8-RA7)/2.)-(RA5+(RA6-RA5)/2.))                MSB 2020
      GBRL = 0.77*BRL1**(-.138)                                         MSB 2030
      AWO1 = BSO*LAWO1                                                  MSB 2040
      AWO3 = BSO*LAWO3                                                  MSB 2050
      AW1  = SQRT(AWO1*APO1)                                            MSB 2060
      AW2  = (AWO1+AWO3)/2.                                             MSB 2070
      AW3  = SQRT(AWO3*APO3)                                            MSB 2080
      GSO1 = QC/AW1                                                     MSB 2090
      GSO2 = QC/AW2                                                     MSB 2100
      GSO3 = QC/AW3                                                     MSB 2110
      BSO=CURVES                                                        MSB 2120
      EQVBSO= CURVES+ 13.*(DIA+DIAI)                                    MSB 2130
      KEY4=0                                                            MSB 2140
10    KEY5=0                                                            MSB 2150
11    ATC = TCI(I) + (TIC/2.0)                                          MSB 2160
      CFT = ATC +CDTF*HSFCT
      ATF = TFO(I)+TIF/2.                                               MSB 2180
      FFT=ATF-FDTF*HSFCT
      FI=I                                                              MSB 2200
      TUBLN(I) =(FI-1.)*BSOI+CURVES                                     MSB 2210
      CVIS=0.2121*EXP(4032./(460.+ATC))                                 MSB 2220
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      CVISW=0.2121*EXP(4032./(460.+CFT))                                MSB 2230
      CDEN=141.37-0.02466*ATC                                           MSB 2240
      CCON=0.240                                                        MSB 2250
      CSPH=0.36                                                         MSB 2260
      FVIS=0.2637*EXP(7362./(460.+ATF))                                 MSB 2270
      FVISW=0.2637*EXP(7362./(460.+FFT))                                MSB 2280
      FDEN=234.97-0.02317*ATF                                           MSB 2290
      FCON=0.70                                                         MSB 2300
      FSPH=0.324                                                        MSB 2310
      VISK = (CVIS/CVISW)**0.14                                         MSB 2320
      FVISK=(FVIS/FVISW)**0.14                                          MSB 2330
      DCVIS = DIA/CVIS                                                  MSB 2340
      CCDEN = 1./CDEN                                                   MSB 2350
      QCCDEN = QC*CCDEN                                                 MSB 2360
C     CALCULATE REYNOLS AND PRANDTL NUMBER TUBE SIDE                    MSB 2550
      RENTO(I)=DIAI*GTO/FVIS                                            MSB 2380
      PRNTO(I)=FVIS*FSPH/FCON                                           MSB 2390
      IF(KENTB.EQ.1.AND.RENTO(I) .GT.1001. .AND.I.NE.1)                 MSB 2400
     1HEFI=1.+((RENTO(I)-1000.)/9000.)**0.5                             MSB 2401
      PDTO(I)=(.0028+.25*RENTO**(-.32))*EQVBSC*GTO**2*HEFI/             MSB 2410
     1       (DIAI*FDEN*417182400.)                                     MSB 2411
C     CALCULATE HEAT TRANSFER COEFF TUBE SIDE                           MSB 2640
      HTO(I)=FCON/DIA*.0217*(RENTO(I)**.8)*(PRNTO(I)**.3333)*FVISK*HEFI MSB 2430
      GO TO 15                                                          MSB 2440
 12   IF(RENTO(I).LT.2100.) GO TO 14                                    MSB 2450
 13   HTO(I) = FCON/DIA*.089*(RENTO(I)**.6666-125.)*(PRNTO(I)**.3333)*  MSB 2460
     1  FVISK*HEFI*(1.+.3333*(DIAI/TUBLN(I))**.6666)                    MSB 2461
      GO TO 15                                                          MSB 2470
 14   HTO(I) = FCON/DIA*(4.36+(0.025*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)    MSB 2480
     1  )/(1.+0.0012*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)))                  MSB 2481
 15   IF(I.EQ.1)GO TO 16                                                MSB 2490
C     CALCULATE FLOW AREAS SHELL SIDE                                   MSB 2480
      VWO1(I) =  QCCDEN/AWO1                                            MSB 2510
      VWO3(I) =  QCCDEN/AWO3                                            MSB 2520
      VM1(I) = GSO1*CCDEN                                               MSB 2530
      VM2(I) = GSO2*CCDEN                                               MSB 2540
      VM3(I) = GSO3*CCDEN                                               MSB 2550
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C     CALCULATE PRESSURE DROPS  SHELL SIDE                              MSB 2590
      DP1 = (1.+.6*RB1)*CDEN*VM1(I)**2                                  MSB 2570
      DP2 = .6*RB2*CDEN*VM2(I)**2                                       MSB 2580
      DP3 = (1.+.6*RB3)*CDEN*VM3(I)**2                                  MSB 2590
      RENSO1(I) = GSO1*DCVIS                                            MSB 2600
      RENSO2(I) = GSO2*DCVIS                                            MSB 2610
      RENSO3(I) = GSO3*DCVIS                                            MSB 2620
      IF(KENTB.EQ.1.AND.RENSO2(I).GT.1001.)                             MSB 2630
     1HEFO=1.+0.3*((RENSO2(I)-1000.)/9000.)**0.5                        MSB 2631
      PDSO(I) = (DP1+DP2+DP3)*PLK*HEFO/834624000.                       MSB 2640
      IF(I.EQ.2)PDSO(1)=PDSO(2)                                         MSB 2650
C     CALCULATE BJ FACTOR AND SHEL SIDE COEFFICIENT                     MSB 2730
      BJ(1) =(0.346*RENSO1(I)**(-0.382))*GBRL                           MSB 2670
      BJ(2) =(0.346*RENSO2(I)**(-0.382))*GBRL                           MSB 2680
      BJ(3) =(0.346*RENSO3(I)**(-0.382))*GBRL                           MSB 2690
      HSO1(I) = (LK*CSPH*GSO1*BJ(1)*((CCON/(CSPH*CVIS))**.66))*VISK     MSB 2700
      HSO2(I) = (LK*CSPH*GSO2*BJ(2)*((CCON/(CSPH*CVIS))**.66))*VISK     MSB 2710
      HSO3(I) = (LK*CSPH*GSO3*BJ(3)*((CCON/(CSPH*CVIS))**.66))*VISK     MSB 2720
      AHSO(I)=(((HSO1(I)*SUM1)+(HSO2(I)*SUM2)+(HSO3(I)*SUM3))/SNT)*HEFO MSB 2730
      GO TO 17                                                          MSB 2740
  16  PDSO(I)=0.                                                        MSB 2750
      APO=3.14159*(RA82-RA52)-SNT*ATUBE                                 MSB 2760
      EQVDIA=4.*APO/(3.14159*SNT*DIA+6.24318*(RA8+RA5))                 MSB 2770
      GSO=QC/APO                                                        MSB 2780
      RENSO   =GSO*DCVIS                                                MSB 2790
      PRESO   =CVIS*CSPH/CCON                                           MSB 2800
      AHSO(I)=0.128*CCON*VISK*(12.*EQVDIA*RENSO   )**0.6                MSB 2810
     1 *PRESO   **0.33/DIA                                              MSB 2811
  17  UOA(I)=1.0/((1.0/AHSO(I))+(1.0/HTC(I))+(1.0/HW))                  MSB 2820
      A = QF*FSPH                                                       MSB 2830
      B = QC*CSPH                                                       MSB 2840
      D = UOA(I)*SNT*BSO   *3.14159*DIA                                 MSB 2850
      P = -HSFCT*(D*(A-B))/(A*B)
      PBAR = EXP(P)                                                     MSB 2870
      C = (B-A)*PBAR                                                    MSB 2880
      TCO(I) = ((TCI(I)*(B*PBAR-A))-(TFC(I)*A*(PBAR-1.)))/C             MSB 2890
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      TFI(I) =((TCO(I)-TCI(I))*B/A) + TFO(I)                            MSB 2900
      HEAT(I) =-A*(TFI(I) - TFO(I))                                     MSB 2910
      TWDT(I) = (HEAT(I)/NTO)*ALOG(DIA/DIAI)/(2.0*3.14159*BSO*WCOND)    MSB 2920
      CTIF = TFI(I)-TFO(I)                                              MSB 2930
      CTIC = TCO(I)-TCI(I)                                              MSB 2940
      IF((ABS(CTIF-TIF).LE.(3.0)).AND.(ABS(CTIC-TIC).LE.(3.0)))GO TO 18 MSB 2950
      TIF = CTIF                                                        MSB 2960
      TIC = CTIC                                                        MSB 2970
      KEY5=KEY5+1                                                       MSB 2980
      IF(KEY5.GT.50)GO TO 37                                            MSB 2990
      GO TO 11                                                          MSB 3000
 18   THEATO = THEATO + HEAT(I)                                         MSB 3010
      TPDTO = TPDTO + PDTO(I)                                           MSB 3020
      TPDSO = TPDSO + PDSO(I)                                           MSB 3030
      IF(I.EQ.2)TPDSO=TPDSO+PDSO(1)                                     MSB 3040
      CDTF=(((HEAT(I))  /NTO)/BSO)/(3.14159*DIA*AHSC(I))                MSB 3090
      FDTF=CDTF*AHSO(I)  /HTO(I)                                        MSB 3100
      FWT(I)  =ATF-FDTF*HSFCT
      CWT(I)  =ATC+CDTF*HSFCT
      AVWT(I)  =0.5*(FWT(I)  +CWT(I))                                   MSB 3130
      TSUM=TSUM+AVWT(I)                                                 MSB 3140
      SSUM=SSUM+ATC                                                     MSB 3150
      IF(KFINAL.EQ.1.AND.I.EQ.IT) GO TO 20                              MSB 3050
      IF(((ABS(ETF-TFI(I))).LE.((ABS(TFI(I)-TFO(I)))/2.0)).OR.          MSB 3060
     1 (TFI(I).LE.ETF)) GO TO 19                                        MSB 3061
      I=I+1                                                             MSB 3070
      IF(I.GT.75) GO TO 30                                              MSB 3080
      IF(I.EQ.2) ATC1=ATC                                               MSB 3160
      TFO(I) = TFI(I-1)                                                 MSB 3170
      TCI(I) = TCO(I-1)                                                 MSB 3180
      BSO=BSOI                                                          MSB 3190
      EQVBSO=BSO                                                        MSB 3200
      KEY4=KEY4+1                                                       MSB 3210
      IF(KEY4.GT.50)GO TO 36                                            MSB 3220
      GO TO 10                                                          MSB 3230
 19   KFINAL=1                                                          MSB 3240
      IT=I                                                              MSB 3250
      FIT = IT                                                          MSB 3260
```

```
      DCURVE=CURVES*((HEATL-THEATO)/HEAT(1))                            MSB 3270
      CURVES=CURVES+DCURVE                                              MSB 3280
      GO TO 9                                                           MSB 3290
   20 TUBLEN=(FIT-1.)*BSOI+CURVES                                       MSB 3300
      HEXLEN=(FIT-1.)*BSOI+4.*EXPRAD*SIN(ARCR) +DCURVE+0.25*BSMAX       MSB 3310
      STRLEN=(FIT-1.)*BSOI+DCURVE+.25*BSMAX                             MSB 3320
   21 IF(          KTBST.EQ.0) GO TO 24                                 MSB 3330
      T1=FWT(1)                                                         MSB 3340
      T2=CWT(1)                                                         MSB 3350
      PDTO1=PDTO(1)                                                     MSB 3360
      PDSO1=PDSO(1)                                                     MSB 3370
      TSUM=TSUM-AVWT(1)                                                 MSB 3380
      SSUM=SSUM-ATC1                                                    MSB 3390
      TAVT=(CURVES*AVWT(1)+BSOI*TSUM)/TUBLEN                            MSB 3400
      SAVT=((HEXLEN-BSOI*(FIT-1.))*ATC1+BSOI*SSUM)/HEXLEN               MSB 3410
      CALL TUBSTR(TPIN,SPOUT,PDTO1,PDSO1,TPDSO,T1,T2,                   MSB 3420
     1 HEXLEN,EXPRAD,DIAI,DIA,ARC,ETF,FTO,ETC,CTO,SAVT,TAVT,            MSB 3421
     2 T11,T12,T13,T24,T25,T36,T37,T38,T49,T410,DT,  BM,ASM,            MSB 3422
     3 ST,STP,SQP,SLPR,SLPG,SLLO,SLLI,STTO,STTI,TM,CASM,CTM,            MSB 3423
     4 P1,P2,SA,R1,R2,TL,RB,  AA1,AA2,AA3,AA4,AA5,BB1,BB2,              MSB 3424
     5 BB3,BB4,BB5)                                                     MSB 3425
      KEY3=KEY3+1                                                       MSB 3430
      IF(KEY3.GT.50)GO TO 35                                            MSB 3440
      IF(T24.LT.0.0.OR.T12.LT.0.0) GO TO 22                             MSB 3450
      IF(T24.GT.(.08*ASM).AND.T12.GT.(.08*ASM)) GO TO 23                MSB 3460
      GO TO 24                                                          MSB 3470
   22 XPRMIN=EXPRAD                                                     MSB 3480
      GO TO 8                                                           MSB 3490
   23 XPRMAX=EXPRAD                                                     MSB 3500
      GO TO 8                                                           MSB 3510
   24 VOL = 0.7854*(DIAI**2.0)*NTO*TUBLEN                               MSB 3520
C     CHECK OF TUBE AND SHELL PRESSURE DROPS                            MSB 3250
      KEY2 = KEY2 + 1                                                   MSB 3540
      IF(PERC2.LE.0.1) GO TO 33                                         MSB 3550
      IF(TPDTO.LT.(PERC2*PRDT)) GO TO 25                                MSB 3560
      IF(TPDTO.GT.PRDT) GO TO 26                                        MSB 3570
      GO TO 27                                                          MSB 3580
```

```
 25    IF(RA8.LE.(RA5   +0.005)) GO TO 34                                 MSB 3590
       RA8H  =RA8                                                         MSB 3600
       IF(KEY2.NE.30)GO TO 3                                              MSB 3610
       RA8L=RA8L-0.2                                                      MSB 3620
       PERC2 = PERC2 - 0.01                                               MSB 3630
       KEY2=10                                                            MSB 3640
       GO TO 3                                                            MSB 3650
 26    IF(RA8.GE.(RA8MAX-0.005)) GO TO 34                                 MSB 3660
       RA8L  =RA8                                                         MSB 3670
       IF(KEY2.NE.30) GO TO 3                                             MSB 3680
       RA8H=RA8H+0.2                                                      MSB 3690
       PERC2 = PERC2 - 0.01                                               MSB 3700
       KEY2=10                                                            MSB 3710
       GO TO 3                                                            MSB 3720
 27    KEY1 = KEY1 + 1                                                    MSB 3730
       IF(PERC1.LE.0.1) GO TO 32                                          MSB 3760
       IF(TPDSO.LT.(PERC1*PRDS)) GO TO 28                                 MSB 3770
       IF(TPDSO.GT.PRDS)GO TO 29                                          MSB 3780
       GO TO 38                                                           MSB 3790
 28    IF(BSOI.LE.(BSMIN+0.005))GO TO 31                                  MSB 3800
       BSH  =BSOI                                                         MSB 3810
       IF(KEY1.NE.30)GO TO 2                                              MSB 3820
       BSL=BSL-0.1                                                        MSB 3830
       PERC1 = PERC1 - 0.01                                               MSB 3840
       KEY1=10                                                            MSB 3850
       GO TO 2                                                            MSB 3860
 29    IF(BSOI.GE.(BSMAX-0.005))GO TO 31                                  MSB 3870
       BSL  =BSOI                                                         MSB 3880
       IF(KEY1.NE.30) GO TO 2                                             MSB 3890
       BSH=BSH+0.1                                                        MSB 3900
       PERC1 = PERC1 - 0.01                                               MSB 3910
       KEY1=10                                                            MSB 3920
       GO TO 2                                                            MSB 3930
C                                                                         MSB 3640
C      PRINT EXIT SIGNALS                                                 MSB 3650
 30    PRINT 1051,BSO                                                     MSB 3960
 1057  FORMAT(39H1BAFFLE SPACINGS EXCEEDE 75 WITH BSO = ,F5.2,2X,4H(FT)) MSB 3970
       GO TO 38                                                           MSB 3980
```

```
31    PRINT 1052                                                      MSB 3990
1058  FORMAT(20H1BSOI = MAX. OR MIN.)                                 MSB 4000
      GO TO 38                                                        MSB 4010
32    PRINT 1059                                                      MSB 4020
1059  FORMAT(48H1 PERC1 FOR SHELL PRESSURE DROP IS LESS THEN 0.1)     MSB 4030
      GO TO 38                                                        MSB 4040
33    PRINT 1060                                                      MSB 4050
1060  FORMAT(48H1 PERC2 FOR  TUBE PRESSURE DROP IS LESS THEN 0.1)     MSB 4060
      GO TO 38                                                        MSB 4070
34    PRINT 1061                                                      MSB 4080
1061  FORMAT(29H1 SHELL RADIUS = MAX. OR MIN.)                        MSB 4090
      GO TO 38                                                        MSB 4100
35    PRINT 1062, KEY3                                                MSB 4110
1062  FORMAT(6H1KEY3= ,I5)                                            MSB 4120
      GO TO 38                                                        MSB 4130
36    PRINT 1063, KEY4                                                MSB 4140
1063  FORMAT(6H1KEY4= ,I5)                                            MSB 4150
      GO TO 38                                                        MSB 4160
37    PRINT 1064, KEY5                                                MSB 4170
1064  FORMAT(6H1KEY5= ,I5)                                            MSB 4180
      GO TO 38                                                        MSB 4190
C                                                                     MSB 3810
C     END OF CASE, PRINT OUTPUT                                       MSB 3820
38    DO 39 I = 1,IT                                                  MSB 4220
      V1(I)  = VM1(I)*GFTT                                            MSB 4230
      V2(I)  = VM2(I)*GFTT                                            MSB 4240
      V3(I)  = VM3(I)*GFTT                                            MSB 4250
      VW1(I) = VWO1(I)*GFTT                                           MSB 4260
      VW3(I) = VWO3(I)*GFTT                                           MSB 4270
39    CONTINUE                                                        MSB 4280
      TTDSO = TPDSO*GFT                                               MSB 4290
      TTDTO = TPDTO*GFT                                               MSB 4300
      TPPERC=TPDTO*100./PRDT                                          MSB 4310
      SPPERC=TPDSO*100./PRDS                                          MSB 4320
      HTPERC=100.*THEATO/HEATL                                        MSB 4330
      AREA=3.14159*DIA*SNT*TUBLEN                                     MSB 4340
```

```
      ASM3=3.*ASM                                                       MSB 4350
      PSTO=AA1                                                          MSB 4360
      PQSTO=AA2                                                         MSB 4370
      PQFSTO=AA3                                                        MSB 4380
      PSTI=BB1                                                          MSB 4390
      PQSTI=BB4                                                         MSB 4400
      PQFSTI=BB5                                                        MSB 4410
C                                                                       MSB 1640
      PRINT 1033,THEATO,HTPERC                                          MSB 4430
      PRINT 1034, QC                                                    MSB 4440
      PRINT 1035, QF                                                    MSB 4450
      PRINT 1036,TTDSO,SPPERC                                           MSB 4460
      PRINT 1037, TTDTO,TPPERC                                          MSB 4470
      PRINT 1038,RA8                                                    MSB 4480
      PRINT 1039,BSOI                                                   MSB 4490
      PRINT 1040,VCL                                                    MSB 4500
      PRINT 1041, AREA                                                  MSB 4510
      PRINT 1042,SNT                                                    MSB 4520
      PRINT 1043,TUBLEN                                                 MSB 4530
      PRINT 1044, HEXLEN                                                MSB 4540
      PRINT 1045, STRLEN                                                MSB 4550
      PRINT 1046,EXPRAD                                                 MSB 4560
      PRINT 1047, GBRL                                                  MSB 4570
      PRINT 1051 ,TAVT                                                  MSB 4580
      PRINT 1052 ,SAVT                                                  MSB 4590
      PRINT 1053,PSTO,PSTI,ASM                                          MSB 4600
      PRINT 1054,PQSTO,PQSTI,ASM3                                       MSB 4610
      PRINT 1055,PQFSTO,PQFSTI,SA                                       MSB 4620
      PRINT 1048, (I,(TCI(I),TCO(I),CWT(I), TFI(I),TFC(I),FWT(I),       MSB 4630
     1       TWDT(I) ),I=1,IT)                                          MSB 4631
      PRINT 1049,(I,(V1(I),V2(I),V3(I),VW1(I),VW3(I),PDSO(I),PDTO(I)),  MSB 4640
     1   I=1,IT)                                                        MSB 4641
      PRINT 1050,(I,(RENTO(I),PRNTO(I),RENSO1(I),RENSC2(I),RENSO3(I),   MSB 4650
     1HTO(I),AHSO(I) ,UOA(I),HEAT(I)),I=1,IT)                           MSB 4651
C                                                                       MSB 4240
C     LOOP FOR ADDITIONAL CASES IF REQUIRED                             MSB 4250
   40 CONTINUE                                                          MSB 4680
```

```
      KEY7=KEY7+1                                                       MSB 4690
      IF(KEY7.GT.KASES)GO TO 41                                         MSB 4700
      GO TO 1                                                           MSB 4710
   41 CONTINUE                                                          MSB 4720
      END                                                               MSB 4730
```

```
      SUBROUTINE TUBSTR(TPIN,SPOUT,PDTO1,PDSO1,TPDSO,T1,T2,             TUBST 10
     1 HEXLEN,EXPRAD,DIAI,DIA,ARC,ETF,FTO,ETC,CTO,SAVT,TAVT,            TUBST 11
     2 T11,T12,T13,T24,T25,T36,T37,T38,T49,T410,DT,  BM,ASM,            TUBST 12
     3 ST,STP,SQP,SLPR,SLPG,SLLO,SLLI,STTO,STTI,TM,CASM,CTM,            TUBST 13
     4 P1,P2,SA,R1,R2,TL,RB,  AA1,AA2,AA3,AA4,AA5,BB1,BB2,              TUBST 14
     5 BB3,BB4,BB5)                                                     TUBST 15
      DIMENSION CASM(6),CTM(6)                                          TUBST 20
      GFT=1./144.                                                       TUBST 30
      P1=(TPIN-.5*PDTO1  )*GFT                                          TUBST 40
      P2=(SPOUT     +.5*PDSO1  )*GFT                                    TUBST 50
      R1=6.*DIAI                                                        TUBST 60
      R2=6.*DIA                                                         TUBST 70
      TL   =12.*HEXLEN                                                  TUBST 80
      RB=12.*EXPRAD                                                     TUBST 90
      A=0.017452*ARC                                                    TUBS 100
CC    DETERMINE AVERAGE CHANGE IN TEMPERATURE OF SHELL(DTS) AND TUBE(DTT)    110
      DTS = SAVT-70.                                                    TUBS 120
      DTT = TAVT-70.                                                    TUBS 130
CC    CALCULATE PRESSURE AND TEMPERATURE DIFFERENTIAL ACROSS TUBE WALL, TUBS 140
      DP  = P1-P2                                                       TUBS 150
      DT  = T1-T2                                                       TUBS 160
CC    AND AVERAGE TEMPERATURE OF TUBE WALL                              TUBS 170
      TM  = (T1+T2)/2.                                                  TUBS 180
```

```
CC    CALCULATE MOMENT OF INERTIA OF TUBE CROSSECTICN(AMI)                 TUBS 190
      AMI = 0.785398*(R2**4-R1**4)                                         TUBS 200
CC    CALL SUBROUTINE TO DETERMINE ALLCWABLE STRESS(ASM)                   TUBS 210
      CALL LAGR (CASM,CTM,ASM,TM,2,6    ,IERR)                             TUBS 220
CC    ESTABLISH MATERIAL PROPERTIES CONSTANTS                              TUBS 230
      SA= 25000.0                                                          TUBS 240
      EM  = 25000000.0                                                     TUBS 250
      PR  = 0.3                                                            TUBS 260
      TE  = 0.0000078                                                      TUBS 270
      SE  = 0.0000076                                                      TUBS 280
CC    CALCULATE AXIAL LOAD AND MOMENT DUE TO LCNGITUCNAL EXPANSION         TUBS 290
      DY  = TL*(TE*DTT-SE*DTS)                                             TUBS 300
      RM  = (R2+R1)/2.                                                     TUBS 310
      TW  = R2-R1                                                          TUBS 320
      AL  = TW*RB/RM**2                                                    TUBS 330
      AL2 = AL**2                                                          TUBS 340
      AK  = (1.+12.*AL2)/(10.+12.*AL2)                                     TUBS 350
      AA = 2.*A                                                            TUBS 360
      P = 25000000.*AK*AMI*DY/(RB**3*(AA*COS(AA)-3.*SIN(AA)+4.*A))         TUBS 370
      BM    = P*RB*(1.-COS(A))                                             TUBS 380
CC    CALCULATE Q STRESS DUE TO P                                          TUBS 390
      SQP = -P/(6.28318*RM*TW)                                             TUBS 400
CC    CALCULATE Q STRESS DUE TO M                                          TUBS 410
      B1    = 6./(5.+6.*AL2)                                               TUBS 420
      B2    = BM/(AK*AMI)                                                  TUBS 430
      B3    = (R2/RM)**2                                                   TUBS 440
      B4    = (R1/RM)**2                                                   TUBS 450
      B5    = 1.5*RM*B2*AL*B1                                              TUBS 460
      SLLO = R2*B2*(1.-B1*B3)                                              TUBS 470
      SLLI = R1*B2*(1.-B1*B4)                                              TUBS 480
      STTO = B5*(1.-2.*B3)                                                 TUBS 490
      STTI = B5*(1.-2.*B4)                                                 TUBS 500
CC    CALCULATE F STRESS DUE TO TUBE WALL TEMPERATURE DROP                 TUBS 510
      ST  = 139.*DT                                                        TUBS 520
      SLI = -ST                                                            TUBS 530
      STI = -ST                                                            TUBS 540
      SLO =  ST                                                            TUBS 550
      STO =  ST                                                            TUBS 560
```

```
CC    CALCULATE STRESSES DUE TO PRESSURE                          TUBS 570
CC    HOOP                                                        TUBS 580
      STP = DP*RM/TW                                              TUBS 590
CC    LONGITUDNAL                                                 TUBS 600
      SLPR = STP/2.                                               TUBS 610
      SLPG = 0                                                    TUBS 620
CC    RADIAL                                                      TUBS 630
      SRPI = -P1                                                  TUBS 640
      SRPO = -P2                                                  TUBS 650
CC    P STRESS TUBE OD BEND OD                                    TUBS 660
      A11 =AMAX1(STP,SLPR,SRPO)                                   TUBS 670
      A12 =AMIN1(STP,SLPR,SRPO)                                   TUBS 680
      AA1 = A11-A12                                               TUBS 690
      T11 = ASM- ABS(AA1)                                         TUBS 700
CC    P+Q STRESS TUBE OD BEND OD                                  TUBS 710
      A13 =AMAX1(STP+STTO,SLPR+SQP+SLLO,SRPO)                     TUBS 720
      A14 =AMIN1(STP+STTO,SLPR+SQP+SLLO,SRPO)                     TUBS 730
      AA2 = A13-A14                                               TUBS 740
      T12 = 3*ASM- ABS(AA2)                                       TUBS 750
CC    P+Q+F STRESS TUBE OD BEND OD                                TUBS 760
      A15 =AMAX1(STP+STTO+STO,SLPR+SQP+SLLO+SLO,SRPO)             TUBS 770
      A16 =AMIN1(STP+STTO+STO,SLPR+SQP+SLLO+SLO,SRPO)             TUBS 780
      AA3 = A15-A16                                               TUBS 790
      T13 = SA - ABS(AA3)                                         TUBS 800
CC    P STRESS TUBE OD BEND ID                                    TUBS 810
CC    SAME AS P STRESS AT TUBE OD BEND OD -- T11)                 TUBS 820
CC                                                                TUBS 830
CC    P+Q STRESS TUBE OD BEND ID                                  TUBS 840
      A22 =AMAX1(STP+STTO,SLPR+SQP-SLLO,SRPO)                     TUBS 850
      A23 =AMIN1(STP+STTO,SLPR+SQP-SLLO,SRPO)                     TUBS 860
      AA4 = A22-A23                                               TUBS 870
      T24 = 3*ASM- ABS(AA4)                                       TUBS 880
CC    P+Q+F STRESS TUBE OD BEND ID                                TUBS 890
      A24 =AMAX1(STP+STTO+STO,SLPR+SQP-SLLO+SLO,SRPO)             TUBS 900
      A25 =AMIN1(STP+STTO+STO,SLPR+SQP-SLLO+SLO,SRPO)             TUBS 910
      AA5 = A24-A25                                               TUBS 920
      T25 = SA - ABS(AA5)                                         TUBS 930
```

```
CC    P STRESS TUBE ID BEND OD                                          TUBS 940
      B11 =AMAX1(STP,SLPR,SRPI)                                         TUBS 950
      B12 =AMIN1(STP,SLPR,SRPI)                                         TUBS 960
      BB1 = B11-B1                                                      TUBS 970
      T36 = ASM- ABS(BB1)                                               TUBS 980
CC    P+Q STRESS TUBEID BEND OD                                         TUBS 990
      B13 =AMAX1(STP+STTI,SLPR+SQP+SLLI,SRPI)                           TUB 1000
      B14 =AMIN1(STP+STTI,SLPR+SQP+SLLI,SRPI)                           TUB 1010
      BB2 = B13-B14                                                     TUB 1020
      T37 = 3*ASM- ABS(BB2)                                             TUB 1030
CC    P+Q+F STRESS TUBE ID BEND OD                                      TUB 1040
      B15 =AMAX1(STP+STTI+STI,SLPR+SQP+SLLI+SLI,SRPI)                   TUB 1050
      B16 =AMIN1(STP+STTI+STI,SLPR+SQP+SLLI+SLI,SRPI)                   TUB 1060
      BB3 = B15-B16                                                     TUB 1070
      T38 = SA - ABS(BB3)                                               TUB 1080
CC    P STRESS TUBE ID BEND ID                                          TUB 1090
CC    SAME AS P STRESS AT TUBE ID BEND OD -- T36                        TUB 1100
CC                                                                      TUB 1110
CC    P+Q STRESS TUBE ID BEND ID                                        TUB 1120
      B23 =AMAX1(STP+STTI,SLPR+SQP-SLLI,SRPI)                           TUB 1130
CC                                                                      TUB 1140
      B24 =AMIN1(STP+STTI,SLPR+SQP-SLLI,SRPI)                           TUB 1150
      BB4 = B23-B24                                                     TUB 1160
      T49 = 3*ASM- ABS(BB4)                                             TUB 1170
CC    P+Q+F STRESS TUBE ID BEND ID                                      TUB 1180
      B25  =AMAX1(STP+STTI+STI,SLPR+SQP-SLLI+SLI,SRPI)                  TUB 1190
      B26  =AMIN1(STP+STTI+STI,SLPR+SQP-SLLI+SLI,SRPI)                  TUB 1200
      BB5 = B25-B26                                                     TUB 1210
      T410 = SA - ABS(BB5)                                              TUB 1220
CC                                                                      TUB 1230
CC                                                                      TUB 1240
      RETURN                                                            TUB 1250
      END                                                               TUB 1260
```

```
      SUBROUTINE LAGR (FX,X,FXP,XP,N,NPT,IER)
      DIMENSION FX(NPT),X(NPT)
C     SUBROUTINE USES LAGRANGIAN INTERPOLATICN TC A DESIRED DEGREE
C     POLINOMIAL
C     FX  = FUNCTION OF INDEPENDENT VARIABLE
C     X   = INDEPENTENT VARIABLE
C     FXP = ESTIMATE OF FX AT XP
C     XP  = VALUE OF X FOR WHICH INTERPOLATICN IS DESIRED
C     N   = DEGREE OF POLINOMIAL USED IN INTERPCLATICN
C     NPT = NUMBER OF POINT-PAIRS IN TABLE
C     IER = COUNTER TO REPORT TYPE OF EXECUTICN
C
C     CHECK TO SEE IF XP IS A TABLE ENTRY
      DO 2 K = 1,NPT
      IF(XP.EQ.X(K))1,2
    1 FXP = FX(K)
      IER = 3
      RETURN
    2 CONTINUE
C     DETERMINE IF EXTRAPOLATICN IS REQUIRED
      IF(XP.LT.X(1))4,3
    3 IF(XP.GT.X(NPT))5,6
    4 L1 = 1
      L2 = NPT
      GO TO 15
    5 L1 = NPT - N
      L2 = NPT
      GO TO 15
    6 IER = 2
C     DETERMINE IF SUFFICINT DATA IS PRESENT FOR DEGREE OF POLINOMIAL
      M = N + 1
      IF(M.GT.NPT)7,8
    7 IER = 1
      RETURN
C     DETERMINE NEXT HIGHEST POINT
    8 DO 9 K = 2,NPT
      K1 = K
      IF(XP.LT.X(K))10,9
```

```
  9     CONTINUE
C       DETERMINE THE LOWER POINTS REQUIRED
 10     L  = M/2
 11     L2 = K1 + L - 1
        IF(L2.LE.NPT)13,12
 12     K1 = K1 - 1
        GO TO 11
 13     L1 = K1 + L - M
        IF(L1)14,14,15
 14     K1 = K1 + 1
        L2 = L2 + 1
        GO TO 13
C       INTERPOLATION BY LAGRANGIAN METHCD  (SEE  MATHEMATICS OF PHYSICS
C       AND MODERN ENGINEERING , SOKOLNIKOFF AND REDHEFFER ,PAGES 699,700)
 15     FXP = 0.0
        DO 18  K = L1,L2
        PKX = 1.0
        PKXK = 1.0
        DO 17 I = L1,L2
        IF(I.EQ.K)17,16
 16     PKX = PKX*(XP - X(I))
        PKXK = PKXK*(X(K) - X(I))
 17     CONTINUE
 18     FXP = FXP + FX(K)*PKX/PKXK
        RETURN
        END
```

Intermediate Variables

LAW01	Net cross-flow circumference at inner edge of baffle, ft.
LAW03	Net cross-flow circumference at outer edge of baffle, ft.
NT(I)	Number of tubes in ring I.
BJ(I)	J factor for the heat transfer coefficient at the inner window zone (I = 1), cross-flow zone (I = 2), and outer window zone (I = 3).
HS01(I)	Shell-side heat transfer coefficient for inner window zone in increment I, $Btu/hr \cdot ft^2 \cdot {}^\circ F$.
HS02(I)	Shell-side heat transfer coefficient for cross-flow zone in increment I.
HS03(I)	Shell-side heat transfer coefficient for outer window zone in increment I.
TUBLN(I)	Accumulated tube length up to increment I, ft.
V1(I)	Average velocity of fluid in outer window zone in increment I, ft/sec.
V2(I)	Average velocity of fluid in overlapping baffle zone in increment I.
V3(I)	Average velocity of fluid in inner window zone in increment I.
VW1(I)	Fluid velocity across tubes in outer edge of baffle in increment I, ft/sec.
VW3(I)	Fluid velocity across tubes in inner edge of baffle in increment I.
FTUB	Inside cross-sectional area of tube, ft^2.
KEY1	Flag for number of iterations on baffle spacing.
PERC1	Fraction of input shell-side pressure drop considered acceptable.
KEY2	Flag for number of iterations on outer radius.
PERC2	Fraction of input tube-side pressure drop considered acceptable.
RA8L	Current lower limit for outer radius.
RA8H	Current higher limit for outer radius.
RJ8	Temporary number of tube rings.
IJ8	Integer form of RJ8.
RIJ8	Real form of IJ8.
R(I)	Radius of tube ring I, ft.
FACT(I)	Circumference of tube ring I, ft.
TCPI(I)	Temporary circumferential pitch in tube ring I, ft.

TOTAL(I)	Accumulated number of tubes up to tube ring I.
AVWT(I)	Average temperature of tube wall in increment I, °F.
KEY7	Flag for number of cases performed.
HEFI	Tube-side enhancement factor.
HEFO	Shell-side enhancement factor.
HSFCT	Flag: 1 = tube side hotter than shell side, -1 = tube side colder than shell side.
ARCR	Arc of bent tube for thermal expansion, radians.
ATUBE	Outside cross-sectional area of tube, ft^2.
GFTT	1/3600 .
GFT	1/144 .
DIAI	Inside diameter of tube, ft.
J8	Actual number of tube rings.
TRPI	Actual radial pitch, ft.
CPI	Actual circumferential pitch, ft.
NTO	Integer form of TOTAL(I).
RA52	Square of RA5, ft^2.
RA82	Square of RA8, ft^2.
RA6	Radius of inner baffle edge, ft.
J6	Number of tube rings up to RA6.
RA7	Radius of outer baffle edge, ft.
J7	Number of tube rings up to RA7.
RA62	Square of RA6, ft^2.
RA72	Square of RA7, ft^2.
RB1	Number of tube rings in inner window zone.
RB2	Number of tube rings in cross-flow zone.
RB3	Number of tube rings in outer window zone.
SUM1	Number of tubes in inner window zone.
SUM2	Number of tubes in cross-flow zone.
SUM3	Number of tubes in outer window zone.
ISUM1	Integer form of SUM1.
ISUM2	Integer form of SUM2.
ISUM3	Integer form of SUM3.
BSMAX	Higher limit for baffle spacing, ft.
BSMIN	Lower limit for baffle spacing, ft.

APO1	Net parallel flow in inner window zone, ft^2.
APO3	Net parallel flow in outer window zone, ft^2.
HW	Heat transfer coefficient across tube wall, $Btu/hr \cdot ft^2 \cdot {}^\circ F$.
CSPHAV	Average specific heat in shell side, $Btu/lb \cdot {}^\circ F$.
FSPHAV	Average specific heat in tube side.
GTO	Mass flow rate in tubes, $lb/hr \cdot ft^2$.
KEY3	Flag for number of iterations on tube expansion radius.
XPRMAX	Higher limit on tube expansion radius, ft.
XPRMIN	Lower limit on tube expansion radius, ft.
BSH	Current higher limit for baffle spacing, ft.
BSL	Current lower limit for baffle spacing, ft.
CURVES	An approximate length of the curved section of the tubes, ft.
IT	Number of baffle spacings.
KFINAL	A flag to indicate that the heat load requirement has been met.
TSUM	Accumulated average temperature of tube wall.
SSUM	Accumulated average temperature of shell fluid.
TPDTO	Accumulated tube-side pressure drop.
TPDSO	Accumulated shell-side pressure drop.
TIF	Assumed temperature difference in tube-side fluid between two increments, °F.
TIC	Assumed temperature difference in shell-side fluid between two increments, °F.
CDTF	Tube-side bulk to wall temperature difference, °F.
FDTF	Shell-side bulk to wall temperature difference, °F.
BSO	Current baffle spacing, ft.
GBRL	Correction factor for Bergelin's heat transfer coefficient.
AWO1	Net cross-flow area at inner edge of baffle, ft^2.
AWO3	Net cross-flow area at outer edge of baffle, ft^2.
AW1	Effective flow area in inner window zone, ft^2.
AW2	Effective flow area in cross-flow zone, ft^2.
AW3	Effective flow area in outer window zone, ft^2.
GSO1	Mass flow rate in inner window zone, $lb/hr.ft^2$.
GSO2	Mass flow rate in cross-flow zone, $lb/hr.ft^2$.
GSO3	Mass flow rate in outer window zone, $lb/hr \cdot ft^2$.
EQVBSO	Length of heat exchanger in the curved tube region considered as first baffle spacing.

KEY4	Inactive.
KEY5	Flag for number of iterations on average temperature in each baffle spacing.
ATC	Shell-side average temperature in each baffle spacing, °F.
CFT	Average tube wall temperature on shell side in each baffle spacing, °F.
ATF	Tube-side average temperature in each baffle spacing, °F.
FFT	Average tube wall temperature on tube side in each baffle spacing, °F.
FI	Number of baffle spaces.
CVIS	Shell-side fluid viscosity, lb/ft·sec.
CVISW	CVIS evaluated at wall temperature.
CDEN	Shell-side fluid density, lb/ft^3.
CCON	Shell-side fluid conductivity, Btu/hr.ft.°F.
CSPH	Shell-side fluid specific heat, Btu/lb·°F.
FVIS	Viscosity of tube-side fluid, lb/ft·sec.
FVISW	FVIS evaluated at wall temperature.
FDEN	Density of tube-side fluid, lb/ft^3.
FCON	Conductivity of tube-side fluid, Btu/hr.ft·°F.
FSPH	Specific heat of tube-side fluid, Btu/lb·°F.
VISK	(CVIS/CVISW)**0.14 .
FVISK	(FVIS/FVISW)**0.14 .
DCVIS	DIA/CVIS .
CCDEN	1/CDEN .
QCCDEN	QC*CCDEN .
DP1	Velocity head in inner window zone.
DP2	Velocity head in cross-flow zone.
DP3	Velocity head in outer window zone.
APO	Net flow area parallel to tubes in curved-tube region, ft^2.
EQVDTA	Equivalent diameter to be used in Donohue's correlation, ft.
GSO	Mass flow rate parallel to tubes in curved-tube region, $lb/hr \cdot ft^2$.
RENSO	Reynolds number for shell-side of curved-tube region.
PRESO	Prandtl number for shell-side of curved-tube region.
CTIF	Calculated temperature difference in tube-side fluid between two increments, °F.
CTIC	Calculated temperature difference in shell-side fluid between two increments, °F.

ATC1	Average temperature in shell side of curved-tube region, °F.
FIT	Final number of baffle spaces.
DCURVE	Additional straight length added to the curved-tube section, ft.
PDTO1	Tube-side pressure drop in curved-tube region, lb/ft^2.
PDSO1	Shell-side pressure drop in curved-tube region, lb/ft^2.
T1	Tube-side surface temperature of tube wall, °F.
T2	Shell-side surface temperature of tube wall, °F.
T11	Maximum primary (P) stress test on outside surface of tube at bend OD, psi.
T12	Maximum primary and secondary (P + Q) stress test on outside surface of tube at bend OD, psi.
T13	Maximum peak (P + Q + F) stress test on outside surface of tube at bend OD, psi.
T24	Maximum primary and secondary (P + Q) stress test on outside surface of tube at bend ID, psi.
T25	Maximum peak (P + Q + F) stress test on outside surface of tube at bend ID, psi.
T36	Maximum primary (P) stress test on inside surface of tube at bend OD, psi.
T37	Maximum primary and secondary (P + Q) stress test on inside surface of tube at bend OD, psi.
T38	Maximum peak (P + Q + F) stress test on inside surface of tube at bend OD, psi.
T49	Maximum primary and secondary (P + Q) stress test on inside surface of tube at bend ID, psi.
T410	Maximum peak (P + Q + F) stress test on inside surface of tube at bend ID, psi.
TM	Average temperature of tube wall at point where stresses are determined, °F.
BM	Bending moment resulting from restrained thermal expansion, in.-lb.
ASM	Allowable stress intensity determined in LAGR, psi.
ASM3	Three times ASM, psi.
ST	Magnitude of thermal stress resulting from DT, psi.
STP	Hoop stress resulting from pressure differential across tube wall, psi.
SQP	Longitudinal stress resulting from P, psi.
SLPR	Longitudinal stress resulting from pressure differential across tube wall, psi.
SLPG	Longitudinal stress resulting from pressure differential across lower tube sheet (currently set equal to zero), psi.

SLLO	Magnitude of longitudinal stress resulting from BM on outside diameter of tube, psi.
SLLI	Magnitude of longitudinal stress resulting from BM on inside diameter of tube, psi.
STTO	Magnitude of hoop stress resulting from BM on outside diameter of tube, psi.
STTI	Magnitude of hoop stress resulting from BM on inside diameter of tube, psi.
DT	Temperature differential across tube wall, °F.
P1	Tube-side pressure, psi.
P2	Shell-side pressure, psi.
SA	Allowable stress intensity for cyclic analysis, psi.
R1	Inside radius of tube, in.
R2	Outside radius of tube, in.
TL	Length of tube (difference in elevation of tube ends; HEXLEN in PRIMEX main program), in.
RB	Radius of flexibility bend segments, in.
AA1	Maximum primary (P) stress intensity on outside surface of tube at bend OD, psi.
AA2	Maximum primary and secondary (P + Q) stress intensity on outside surface of tube at bend OD, psi.
AA3	Maximum peak (P + Q + F) stress intensity on outside surface of tube at bend OD, psi.
AA4	Maximum primary and secondary (P + Q) stress intensity on outside surface of tube at bend ID, psi.
AA5	Maximum peak (P + Q + F) stress intensity on outside surface of tube at bend ID, psi.
BB1	Maximum primary (P) stress intensity on inside surface of tube at bend OD, psi.
BB2	Maximum primary and secondary (P + Q) stress intensity on inside surface of tube at bend OD, psi.
BB3	Maximum peak (P + Q + F) stress intensity on inside surface of tube at bend OD, psi.
BB4	Maximum primary and secondary (P + Q) stress intensity on inside surface of tube at bend ID, psi.
BB5	Maximum peak (P + Q + F) stress intensity on inside surface of tube at bend ID, psi.
GFT	Conversion factor, feet to inches.
A	Arc of four bend segments in flexibility bend, radians.

DTS	Average change in temperature of the shell, °F.
DTT	Average change in temperature of the tubes, °F.
DP	Pressure differential across tube wall, psi.
AMI	Moment of inertia of tube cross section, in.^{4}
EM	Modulus of elasticity for tube and shell material, psi.
PR	Poisson's ratio for tube and shell material (0.3).
TE	Coefficient of thermal expansion for tube material, in./in.°F.
SE	Coefficient of thermal expansion for shell material.
DY	Difference in thermal expansion of tubes and shell, in.
RM	Mean radius of tube wall, in.
TW	Thickness of tube wall, in.
AL	Dimensionless parameter in Wahl's factor AK.
AL2	Square of AL.
AK	Wahl's rigidity multiplication factor.
AA	Two times A.
P	Axial load resulting from restrained thermal expansion, lb.
B1, B2, B3, B4, B5	Repeated factors used in calculating stresses resulting from BM.
SLI	Longitudinal stress on inside diameter of tube resulting from temperature differential across tube wall, psi.
STI	Hoop stress on inside diameter of tube resulting from temperature differential across tube wall, psi.
SLO	Longitudinal stress on outside diameter of tube resulting from temperature differential across tube wall, psi.
STO	Hoop stress on outside diameter of tube resulting from temperature differential across tube wall, psi.
SRPI	Radial stress on inside diameter of tube resulting from pressure, psi.
SRPO	Radial stress on outside diameter of tube resulting from pressure, psi.
A11	Maximum value of primary (P) stress on outside surface of tube at bend OD, psi.
A12	Minimum value of primary (P) stress on outside surface of tube at bend OD, psi.
A13	Maximum value of primary and secondary (P + Q) stress on outside surface of tube at bend OD, psi.
A14	Minimum value of primary and secondary (P + Q) stress on outside surface of tube at bend OD, psi.

A15	Maximum value of peak (P + Q + F) stress on outside surface of tube at bend OD, psi.
A16	Minimum value of peak (P + Q + F) stress on outside surface of tube at bend OD, psi.
A22	Maximum value of primary and secondary (P + Q) stress on outside surface of tube at bend ID, psi.
A23	Minimum value of primary and secondary (P + Q) stress on outside surface of tube at bend ID, psi.
A24	Maximum value of peak (P + Q + F) stress on outside surface of tube at bend ID, psi.
A25	Minimum value of peak (P + Q + F) stress on outside surface of tube at bend ID, psi.
B11	Maximum value of primary (P) stress on inside surface of tube at bend OD, psi.
B12	Minimum value of primary (P) stress on inside surface of tube at bend OD, psi.
B13	Maximum value of primary and secondary (P + Q) stress on inside surface of tube at bend OD, psi.
B14	Minimum value of primary and secondary (P + Q) stress on inside surface of tube at bend OD, psi.
B15	Maximum value of peak (P + Q + F) stress on inside surface of tube at bend OD, psi.
B16	Minimum value of peak (P + Q + F) stress on inside surface of tube at bend OD, psi.
B23	Maximum value of primary and secondary (P + Q) stress on inside surface of tube at bend ID, psi.
B24	Minimum value of primary and secondary (P + Q) stress on inside surface of tube at bend ID, psi.
B25	Maximum value of peak (P + Q + F) stress on inside surface of tube at bend ID, psi.
B26	Minimum value of peak (P + Q + F) stress on inside surface of tube at bend ID, psi.

Computer Input for Reference MSBR Primary Heat Exchanger

```
       I         CTM        CASM

       1       800.00    18000.00
       2       900.00    18000.00
       3      1000.00    17000.00
       4      1100.00    13000.00
       5      1200.00     6000.00
       6      1300.00     3500.00

HEAT LOAD REQUIRED =  1899799808.  (BTU/HR)

ALLOWABLE TOTAL TUBE-SIDE PRESSURE DROP =     18720.  (LB/SQ-FT)

ALLOWABLE TOTAL SHELL-SIDE PRESSURE DROP =     16727.  (LB/SQ-FT)

TUBE INLET PRESSURE =     25920.  (LB/SQ-FT)

SHELL OUTLET PRESSURE =     4896.  (LB/SQ-FT)

HIGH TEMP. OF SHELL SIDE FLUID =   1150.00  (F)

HIGH TEMP. OF TUBE SIDE FLUID =   1300.00  (F)

LOW TEMP. OF TUBE SIDE FLUID =   1050.00  (F)

LOW TEMP. OF SHELL SIDE FLUID =   850.00  (F)

HEAT TRANSFER LEAKAGE FACTOR =   0.80000

PRESSURE LEAKAGE FACTOR =    0.52000

CONDUCTIVITY OF TUBE WALL METAL =   11.60000  (BTU/HR-FT-F)
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ARC OF FOUR BENDS FOR FLEXIBILITY =      60.00  (DEGREES)

INSIDE RADIUS OF OUTER ANNULUS =    0.83330  (FEET)

DISTANCE BETWEEN SHELL WALL AND TUBES =    0.03125  (FEET)

MAXIMUM ANTICIPATED OUTER RADIUS OF EXCHANGER =    6.00000  (FEET)

NUMBER OF CASES RUN =    1

USE OF ENHANCED TUBES =    1  (ONE IF ENHANCED TUBES ARE USED)

USE OF STRESS ANALYSIS SUBROUTINE =    1  (ONE IF TO BE USED)

OUTSIDE DIAMETER OF TUBES =    0.03125  (FEET)

WALL THICKNESS OF TUBES =    0.00292  (FEET)

RADIAL PITCH =    0.06250  (FEET)

CIRCUMFERENTIAL PITCH =    0.06250  (FEET)

INNER BAFFLE CUT3  =    0.40000  (PER CENT)

OUTER BAFFLE CUT4  =    0.40000  (PER CENT)
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Computer Output for Reference MSBR Primary Heat Exchanger

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TOTAL HEAT TRANSFERED =  1899564800.  (BTU/HR)  (100.0 PERCENT)

MASS FLOW RATE OF COOLANT =  17590736.  (LB/HR)

MASS FLOW RATE OF FUEL =  23454320.  (LB/HR)

SHELL-SIDE TOTAL PRESSURE DROP =     116.16  (LB/SQIN)  (100.0 PERCENT)

TUBE-SIDE TOTAL PRESSURE DROP =     129.61  (LB/SQIN)  ( 99.7 PERCENT)

NOMINAL SHELL RADIUS =  2.8364  (FT)

UNIFORM BAFFLE SPACING =  0.9356  (FT)

TUBE FLUID VOLUME CONTAINED IN TUBES =   67.38 (CUBIC FEET)

TOTAL HEAT TRANSFER AREA BASED ON TUBE O.D. =     13037.02  (SQFT)

TOTAL NUMBER OF TUBES =  5896.

TOTAL TUBE LENGTH =  22.52  (FT)

HEAT EXCH. APPROX. LENGTH =  21.31  (FEET)

STRAIGHT SECTION OF TUBE LENGTH =  18.35  (FT)

RADIUS OF THERMAL EXPANSION CURVES =   0.86  (FEET)

BERGLIN MODIFICATION FACTOR =  0.80

TUBE WALL AVERAGE TEMP. =    1113.04

SHELL SIDE AVERAGE TEMP. =    1007.83
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P STRESS AT TUBE OD AND TUBE ID =     673.90    636.93 (LB/SQIN)

SHOULD NOT EXCEED   3912.53   )

P+Q STRESS AT TUBE OD AND TUBE ID =   11639.02   8317.50 (LB/SQIN)

SHOULD NOT EXCEED  11737.58   )

P+Q+F STRESS AT TUBE OD AND TUBE ID =   13006.32  10551.26 (LB/SQIN)

SHOULD NOT EXCEED  25000.00   )

  I       TCI          TCO          CWT          TFI          TFO          FWT          TWDT

          F            F            F            F            F            F            F

  1  0.1150E 04  0.1129E 04  0.1254E 04  0.1282E 04  0.1300E 04  0.1271E 04  0.1681E 02
  2  0.1129E 04  0.1115E 04  0.1184E 04  0.1271E 04  0.1282E 04  0.1229E 04  0.4509E 02
  3  0.1115E 04  0.1101E 04  0.1172E 04  0.1259E 04  0.1271E 04  0.1216E 04  0.4495E 02
  4  0.1101E 04  0.1087E 04  0.1159E 04  0.1248E 04  0.1259E 04  0.1204E 04  0.4512E 02
  5  0.1087E 04  0.1074E 04  0.1146E 04  0.1236E 04  0.1248E 04  0.1191E 04  0.4526E 02
  6  0.1074E 04  0.1060E 04  0.1133E 04  0.1225E 04  0.1236E 04  0.1178E 04  0.4538E 02
  7  0.1060E 04  0.1046E 04  0.1119E 04  0.1213E 04  0.1225E 04  0.1165E 04  0.4549E 02
  8  0.1046E 04  0.1032E 04  0.1106E 04  0.1201E 04  0.1213E 04  0.1152E 04  0.4557E 02
  9  0.1032E 04  0.1018E 04  0.1093E 04  0.1190E 04  0.1201E 04  0.1139E 04  0.4564E 02
 10  0.1018E 04  0.1004E 04  0.1080E 04  0.1178E 04  0.1190E 04  0.1126E 04  0.4568E 02
 11  0.1004E 04  0.9895E 03  0.1067E 04  0.1166E 04  0.1178E 04  0.1112E 04  0.4571E 02
 12  0.9895E 03  0.9754E 03  0.1054E 04  0.1155E 04  0.1166E 04  0.1099E 04  0.4571E 02
 13  0.9754E 03  0.9614E 03  0.1040E 04  0.1143E 04  0.1155E 04  0.1086E 04  0.4569E 02
 14  0.9614E 03  0.9474E 03  0.1027E 04  0.1131E 04  0.1143E 04  0.1073E 04  0.4566E 02
 15  0.9474E 03  0.9334E 03  0.1014E 04  0.1119E 04  0.1131E 04  0.1059E 04  0.4560E 02
 16  0.9334E 03  0.9194E 03  0.1001E 04  0.1108E 04  0.1119E 04  0.1046E 04  0.4551E 02
 17  0.9194E 03  0.9054E 03  0.9874E 03  0.1096E 04  0.1108E 04  0.1033E 04  0.4541E 02
 18  0.9054E 03  0.8915E 03  0.9742E 03  0.1085E 04  0.1096E 04  0.1019E 04  0.4529E 02
 19  0.8915E 03  0.8776E 03  0.9610E 03  0.1073E 04  0.1085E 04  0.1006E 04  0.4514E 02
 20  0.8776E 03  0.8638E 03  0.9479E 03  0.1061E 04  0.1073E 04  0.9929E 03  0.4497E 02
 21  0.8638E 03  0.8500E 03  0.9348E 03  0.1050E 04  0.1061E 04  0.9796E 03  0.4479E 02
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  I        V1         V2         V3         VW1        VW3        PDSO        PDTO

                               FT/SEC                              LB/SQFT

  1      0.0        0.0        0.0        0.0        0.0        851.3384   3430.7144
  2      6.1660     7.0071     6.7107     6.4319     7.6953     851.3384    834.3669
  3      6.1475     6.9861     6.6905     6.4126     7.6722     845.2434    826.6611
  4      6.1292     6.9653     6.6706     6.3935     7.6493     839.1812    818.9949
  5      6.1109     6.9445     6.6507     6.3744     7.6265     833.1099    811.3169
  6      6.0927     6.9238     6.6309     6.3554     7.6038     827.0310    803.6326
  7      6.0745     6.9032     6.6112     6.3365     7.5812     820.9490    795.9424
  8      6.0565     6.8826     6.5915     6.3176     7.5586     814.8638    788.2510
  9      6.0384     6.8621     6.5719     6.2988     7.5361     808.7805    780.5627
 10      6.0205     6.8418     6.5523     6.2801     7.5137     802.6997    772.8799
 11      6.0027     6.8215     6.5329     6.2615     7.4914     796.6255    765.2080
 12      5.9849     6.8013     6.5136     6.2430     7.4693     790.5603    757.5488
 13      5.9673     6.7812     6.4944     6.2246     7.4473     784.5063    749.9067
 14      5.9497     6.7613     6.4753     6.2063     7.4254     778.4670    742.2856
 15      5.9323     6.7415     6.4564     6.1881     7.4036     772.4438    734.6880
 16      5.9150     6.7219     6.4375     6.1701     7.3821     766.4417    727.1172
 17      5.8979     6.7024     6.4189     6.1522     7.3606     760.4609    719.5779
 18      5.8808     6.6830     6.4003     6.1344     7.3394     754.5051    712.0718
 19      5.8639     6.6638     6.3819     6.1168     7.3183     748.5771    704.6025
 20      5.8472     6.6448     6.3637     6.0994     7.2974     742.6804    697.1743
 21      5.8306     6.6260     6.3457     6.0821     7.2768     736.8167    689.7888
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  I      RENTO        PRNTO        RENSO1       RENSO2       RENSC3        HTO          AHSO          UOA          HEAT
                                                                                   BTU/HR/SQFT/F               BTU/HR

  1  0.1129E 05  0.8172E 01  0.0         0.0         0.0         0.2958E 04  0.5273E 03  0.3980E 03  0.1332E 09
  2  0.1090E 05  0.8463E 01  0.2908E 05  0.3304E 05  0.3164E 05  0.3421E 04  0.2605E 04  0.1048E 04  0.8775E 08
  3  0.1059E 05  0.8707E 01  0.2843E 05  0.3231E 05  0.3094E 05  0.3317E 04  0.2552E 04  0.1029E 04  0.8748E 08
  4  0.1029E 05  0.8960E 01  0.2779E 05  0.3158E 05  0.3024E 05  0.3244E 04  0.2526E 04  0.1018E 04  0.8780E 08
  5  0.9998E 04  0.9225E 01  0.2715E 05  0.3085E 05  0.2954E 05  0.3172E 04  0.2500E 04  0.1006E 04  0.8807E 08
  6  0.9706E 04  0.9503E 01  0.2651E 05  0.3012E 05  0.2885E 05  0.3100E 04  0.2474E 04  0.9950E 03  0.8832E 08
  7  0.9418E 04  0.9794E 01  0.2587E 05  0.2940E 05  0.2815E 05  0.3029E 04  0.2448E 04  0.9833E 03  0.8853E 08
  8  0.9134E 04  0.1010E 02  0.2523E 05  0.2868E 05  0.2746E 05  0.2959E 04  0.2421E 04  0.9716E 03  0.8869E 08
  9  0.8854E 04  0.1042E 02  0.2460E 05  0.2796E 05  0.2677E 05  0.2889E 04  0.2395E 04  0.9597E 03  0.8882E 08
 10  0.8578E 04  0.1075E 02  0.2397E 05  0.2724E 05  0.2609E 05  0.2820E 04  0.2368E 04  0.9476E 03  0.8890E 08
 11  0.8307E 04  0.1110E 02  0.2335E 05  0.2653E 05  0.2541E 05  0.2751E 04  0.2341E 04  0.9355E 03  0.8895E 08
 12  0.8041E 04  0.1147E 02  0.2273E 05  0.2583E 05  0.2473E 05  0.2684E 04  0.2314E 04  0.9233E 03  0.8896E 08
 13  0.7779E 04  0.1186E 02  0.2211E 05  0.2513E 05  0.2406E 05  0.2617E 04  0.2287E 04  0.9109E 03  0.8892E 08
 14  0.7523E 04  0.1226E 02  0.2150E 05  0.2443E 05  0.2340E 05  0.2551E 04  0.2259E 04  0.8985E 03  0.8885E 08
 15  0.7271E 04  0.1268E 02  0.2089E 05  0.2374E 05  0.2274E 05  0.2485E 04  0.2232E 04  0.8860E 03  0.8873E 08
 16  0.7025E 04  0.1313E 02  0.2029E 05  0.2306E 05  0.2209E 05  0.2421E 04  0.2204E 04  0.8733E 03  0.8857E 08
 17  0.6784E 04  0.1360E 02  0.1970E 05  0.2239E 05  0.2144E 05  0.2357E 04  0.2177E 04  0.8607E 03  0.8837E 08
 18  0.6548E 04  0.1409E 02  0.1912E 05  0.2172E 05  0.2080E 05  0.2295E 04  0.2149E 04  0.8479E 03  0.8813E 08
 19  0.6318E 04  0.1460E 02  0.1854E 05  0.2107E 05  0.2018E 05  0.2233E 04  0.2122E 04  0.8351E 03  0.8785E 08
 20  0.6094E 04  0.1514E 02  0.1797E 05  0.2042E 05  0.1955E 05  0.2172E 04  0.2094E 04  0.8223E 03  0.8752E 08
 21  0.5874E 04  0.1570E 02  0.1740E 05  0.1978E 05  0.1894E 05  0.2112E 04  0.2067E 04  0.8094E 03  0.8716E 08
```

Appendix C

THE RETEX PROGRAM

The RETEX computer program is outlined in block-diagram form in Fig. C.1. The input data required for the program are given in Table C.1, and the output received from the program are given in Table C.2. A complete listing of the main program is followed by definitions of the intermediate variables used in the program. To illustrate the use of the RETEX program, the input and output for the MSBR steam reheater exchanger discussed in Subsection 3.1 of this report are presented as printed by the computer.

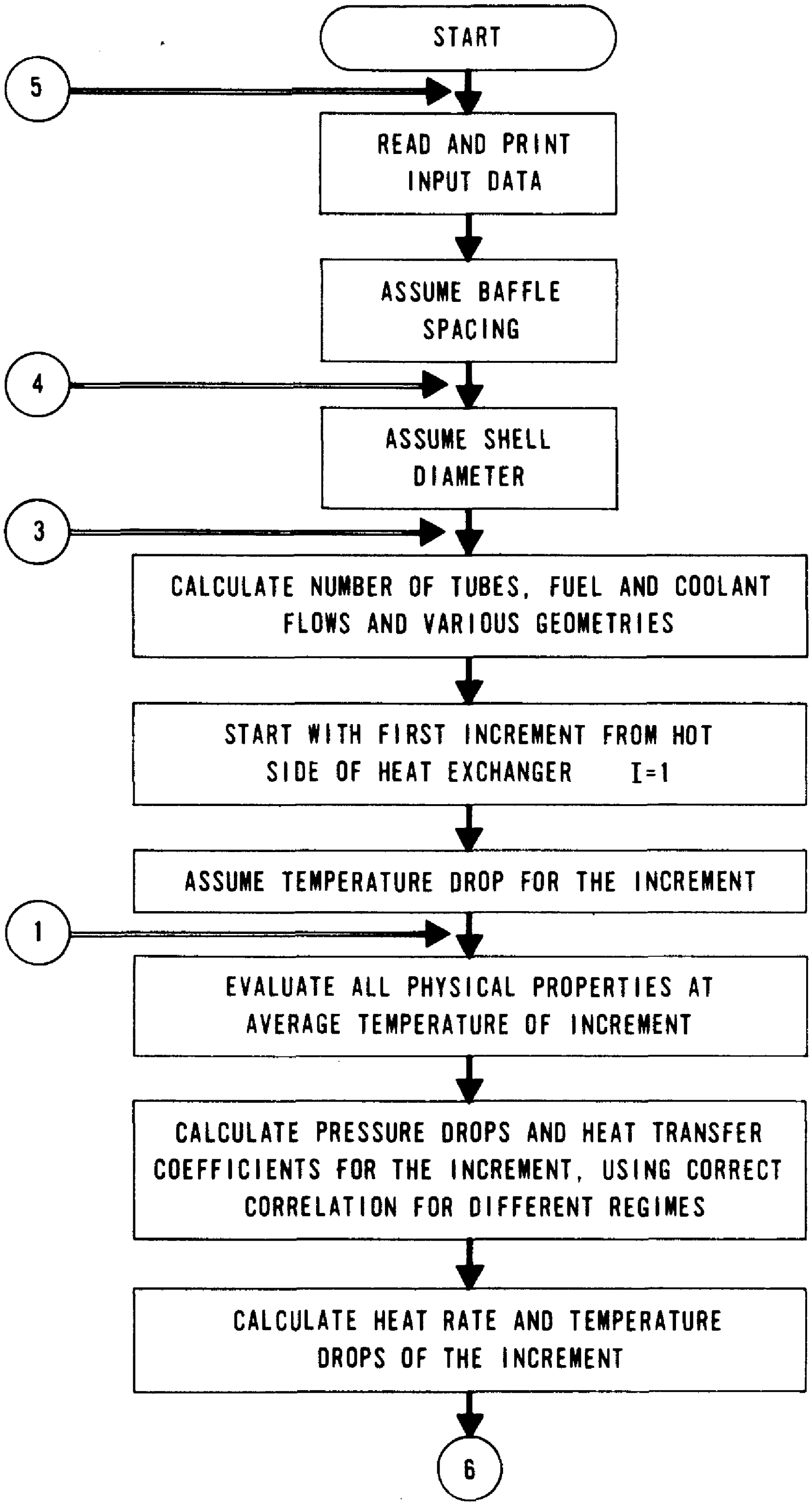

Fig. C.1. Simplified Flow Diagram of the RETEX Computer Program.

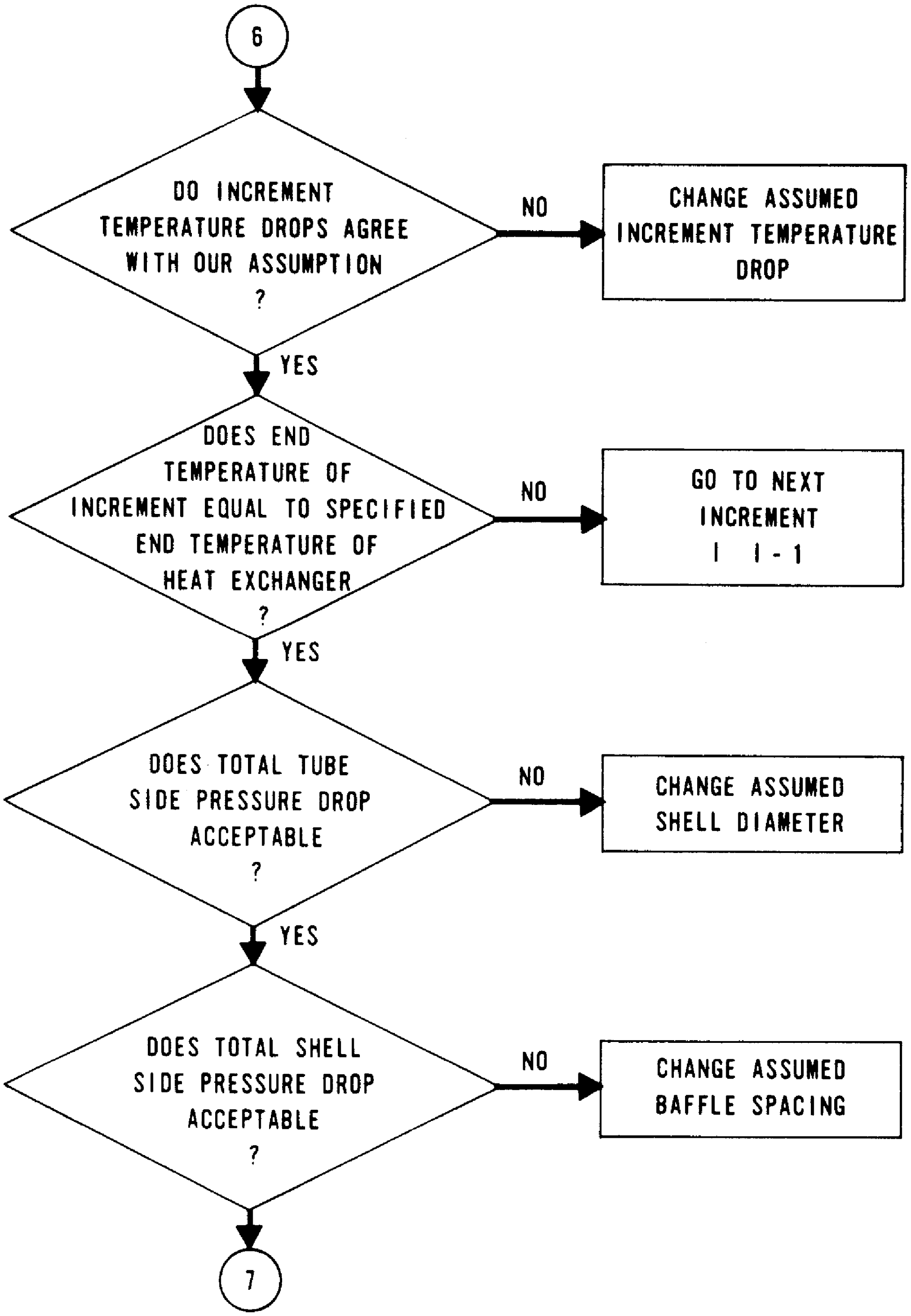

Fig. C.1. (continued)

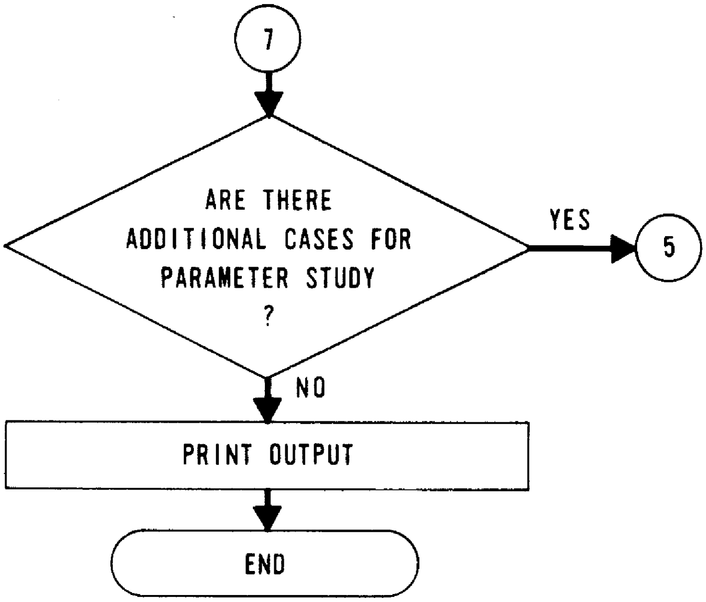

Fig. C.1. (continued)

Table C.1. Computer Input Data for RETEX Program

Card	Columns	Format	Variable	Term	Units
A	1-10	E10.4	Heat load required	HEATL	Btu/hr
	11-20	F10.0	Allowable tube-side pressure drop	PRDT	lb/ft^2
	21-30	F10.0	Allowable shell-side pressure drop	PRDS	lb/ft^2
B	1-10	F10.0	Coolant outlet temperature	CTO	°F
	11-20	F10.0	Fuel inlet temperature	FTO	°F
	21-30	F10.0	Fuel outlet temperature	ETF	°F
	31-40	F10.0	Coolant inlet temperature	ETC	°F
C	1-10	F10.0	Leakage factor for heat transfer correlations	LK	
	11-20	F10.0	Leakage factor for pressure drop calculations	PLK	
	21-30	F10.0	Tube material conductivity	WCOND	Btu/hr•ft•°F
D	1-10	F10.0	Radius of coolant central downcomer	RA5	ft
	11-20	F10.0	Distance between shell wall and tube bundle	DTR	ft
	21-30	F10.0	Maximum anticipated heat exchanger radius	RA8MAX	ft
	31-35	I5	Number of cases to be run	KASES	
	36-40	I5	Index one if enhanced tubes are used	KENTB	
$E_1, E_2,$ ... E_{KASES}	1-10	F10.0	Outside diameter of tube	DIA	ft
	11-20	F10.0	Tube wall thickness	WTHK	ft
	21-30	F10.0	Triangular pitch	TPIP	ft
	31-40	F10.0	Inner baffle cut	CUT3	% of area
	41-50	F10.0	Outer baffle cut	CUT4	% of area

Table C.2. Output Data From RETEX Computer Program

Term	Variable	Units
THEATO	Total heat actually transferred	Btu/hr
HTPERC	Percentage of required heat load transferred	
QC	Coolant (shell-side) mass flow rate	lb/hr
QF	Fuel (tube-side) mass flow rate	lb/hr
TTDSO	Total tube-side pressure drop	psi
SPPERC	Percentage of allowed tube pressure drop actually used	
TTDTU	Total shell-side pressure drop	psi
TPPERC	Percentage of allowed shell pressure drop actually used	
RA8	Radius of heat exchanger shell	ft
BSOI	Distance between baffles	ft
VOL	Fluid volume contained in tubes	ft^3
AREA	Total heat transfer area in heat exchanger	ft^2
SNT	Total number of tubes	
TUBLEN	Actual tube length	ft
GBRL	Modification factor for Bergelin's heat transfer correlation	
SAVT	Shell average temperature	°F
TAVT	Tube average temperature	°F
TCI(I)	Coolant outlet temperature from increment I	°F
TCO(I)	Coolant inlet temperature from increment I	°F
CWT(I)	Average tube wall temperature at coolant side	°F
TFI(I)	Fuel outlet temperature from increment I	°F
TFO(I)	Fuel inlet temperature from increment I	°F
FWT(I)	Average tube wall temperature at fuel side	°F
TWDT(I)	Average temperature drop across tube wall in increment I	°F
V1(I)	Fluid average velocity in outer window in increment I	ft/sec
V2(I)	Fluid average velocity in overlapping baffle zone in increment I	ft/sec
V3(I)	Fluid average velocity in inner window in increment I	ft/sec

Table C.2 (continued)

Term	Variable	Units
VW1(I)	Fluid velocity across tubes in outer edge of baffle in increment I	ft/sec
VW3(I)	Fluid velocity across tubes in inner edge of baffle in increment I	ft/sec
PDSO(I)	Shell-side pressure drop for increment I	lb/ft^2
PDTO(I)	Tube-side pressure drop for increment I	lb/ft^2
RENTO(I)	Tube-side Reynolds number for increment I	
PRNTO(I)	Tube-side Prandtl number for increment I	
RENSO1(I)	Reynolds number in outer window in increment I	
RENSO2(I)	Reynolds number in overlapping baffle zone in increment I	
RENSO3(I)	Reynolds number in inner window in increment I	
HTO(I)	Tube-side heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
AESO(I)	Shell-side heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
UOA(I)	Overall heat transfer coefficient in increment I	$Btu/hr \cdot ft^2 \cdot °F$
HEAT(I)	Heat transferred in increment I	Btu/hr

The RETEX Program Listing

```
**FTN,L,E,G,M.
      PROGRAM MSBRPE-2                                                  MSBRP 10
      TYPE REAL     LK ,LAWO1 , LAWO3                                   MSBRP 20
      DIMENSION TFO(130),TCI(130),VM1(130),VM2(130),VWO1(130),VWO3(130),MSBRP 30
     1   RENTO(130),PRNTO(130),RENSO1(130),RENSO3(130), RENSO2(130),    MSBRP 31
     2   VM3(130),PDSO(130),NT(100),BJ(3),HSO1(130),HSO2(130),HSO3(130),MSBRP 32
     3AHSO(130),HTC(130),UOA(130),TCO(130),TFI(130),HEAT(130),TWDT(130),MSBRP 33
     4 PDTO(130),TUBLN(130),V1(130),V2(130),V3(130),VW1(130),VW3(130),  MSBRP 34
     5 R(100),FACT(100),TCPI(100),TCTAL(100)                            MSBRP 35
     6  CWT(130),FWT(130),AVWT(130)                                     MSBRP 36
 1001 FORMAT( E10.4, 2F10.0)                                            MSBRP 40
 1002 FORMAT( 4F10.0)                                                   MSBRP 50
 1003 FORMAT( 3F10.0)                                                   MSBRP 60
 1004 FORMAT( 3F10.0,2I5)                                               MSBRP 70
 1005 FORMAT( 5F10.0)                                                   MSBRP 80
 1006 FORMAT(22H0HEAT LOAD REQUIRED = ,F12.0,2X,8H(BTU/HR))             MSBRP 90
 1007 FORMAT(43H0ALLOWABLE TOTAL TUBE-SIDE PRESSURE DROP = ,F10.0,2X,   MSBR 100
     1  10H(LB/SQ-FT) )                                                 MSBR 101
 1008 FORMAT(44H0ALLOWABLE TOTAL SHELL-SIDE PRESSURE DROP = ,F10.0,2X,  MSBR 110
     1  10H(LB/SQ-FT) )                                                 MSBR 111
 1009 FORMAT(33H0HIGH TEMP. OF SHELL SIDE FLUID =,F10.2,2X,3H(F))       MSBR 120
 1010 FORMAT(33H0HIGH TEMP. OF TUBE SIDE FLUID =  ,F10.2,2X,3H(F))      MSBR 130
 1011 FORMAT(32H0LOW TEMP. OF TUBE SIDE FLUID =  ,F10.2,2X,3H(F))       MSBR 140
 1012 FORMAT(32H0LOW TEMP. OF SHELL SIDE FLUID =,F10.2,2X,3H(F))        MSBR 150
 1013 FORMAT(32H0HEAT TRANSFER LEAKAGE FACTOR = ,F10.5)                 MSBP 160
 1014 FORMAT(27H0PRESSURE LEAKAGE FACTOR = ,F10.5 )                     MSBR 170
 1015 FORMAT(35H0CONDUCTIVITY OF TUBE WALL METAL = ,F10.5,2X,           MSBR 180
     1  13H(BTU/HR-FT-F) )                                              MSBR 181
 1016 FORMAT(34H0INSIDE RADIUS OF OUTER ANNULUS = ,F10.5,2X,6H(FEET))   MSBR 190
 1017 FORMAT(41H0DISTANCE BETWEEN SHELL WALL AND TUBES =                MSBR 200
     1 ,F10.5,2X,6H(FEET))                                              MSBR 201
 1018 FORMAT(49H0MAXIMUM ANTICIPATED OUTER RADIUS OF EXCHANGER = ,      MSBR 210
     1      F10.5,2X,6H(FEET) )                                         MSBR 211
```

```
 1019 FORMAT(23H0NUMBER OF CASES RUN = ,I4)                           MSBR 220
 1020 FORMAT(25H0USE OF ENHENCED TUBES = ,I4,2X,32H(ONE IF ENHENCED TUBEMSBR 230
     1S ARE USED))                                                    MSBR 231
 1021 FORMAT(29H0OUTSIDE DIAMETER OF TUBES = ,F10.5,2X,  6H(FEET) )    MSBR 240
 1022 FORMAT(27H0WALL THICKNESS OF TUBES = ,F10.5,2X,  6H(FEET) )      MSBR 250
 1023 FORMAT(20H0TRIANGULAR PITCH = ,     F10.5,2X,  6H(FEET))         MSBR 260
 1024 FORMAT(22H0INNER BAFFLE CUT3  = ,F10.5,2X, 10H(PER CENT) )       MSBR 270
 1025 FORMAT(22H0OUTER BAFFLE CUT4  = ,F10.5,2X, 10H(PER CENT) )       MSBR 280
 1026 FORMAT(25H1TOTAL HEAT TRANSFERED = ,F12.0,2X,8H(BTU/HR),         MSBR 290
     1      2X,1H(,F5.1,9H PERCENT))                                  MSBR 291
 1027 FORMAT(29H0MASS FLOW RATE OF COOLANT = ,F10.0,2X, 7H(LB/HR) )    MSBR 300
 1028 FORMAT(26H0MASS FLOW RATE OF FUEL = ,F10.0,2X, 7H(LB/HR) )       MSBR 310
 1029 FORMAT(34H0SHELL-SIDE TOTAL PRESSURE DROP = ,F10.2,2X, 9H(LB/SQIN)MSBR 320
     1      ,2X,1H(,F5.1,9H PERCENT))                                 MSBR 321
 1030 FORMAT(33H0TUBE-SIDE TOTAL PRESSURE DROP = ,F10.2,2X, 9H(LB/SQIN),MSBR 330
     1      2X,1H(,F5.1,9H PERCENT))                                  MSBR 331
 1031 FORMAT(24H0NOMINAL SHELL RADIUS = ,F7.4,2X,4H(FT))               MSBR 340
 1032 FORMAT(26H0UNIFORM BAFFLE SPACING = ,F7.4,2X,4H(FT))             MSBR 350
 1033 FORMAT(40H0TUBE FLUID VOLUME CONTAINED IN TUBES = ,F7.2,1X,      MSBR 360
     112H(CUBIC FEET))                                                MSBR 361
 1034 FORMAT(1H0,46HTOTAL HEAT TRANSFER AREA BASED ON TUBE O.D. = ,    MSBR 370
     1   F12.2,2X,6H(SQFT))                                           MSBR 371
 1035 FORMAT(25H0TOTAL NUMBER OF TUBES = ,F6.0)                        MSBR 380
 1036 FORMAT(21H0TOTAL TUBE LENGTH = ,F6.2,2X,4H(FT))                  MSBR 390
 1037 FORMAT(23H0BWINDOW 1 CROSSFLOW = ,F5.2,2X,6H(SQFT))              MSBR 400
 1038 FORMAT(31H0BERGLIN MODIFICATION FACTOR = ,F5.2)                  MSBR 410
 1039 FORMAT(1H0,2X,1HI,7X,3HTCI,9X,3HTCO,9X,3HCWT,9X, 3HTFI,9X,3HTFO,  MSBR 420
     19X,3HFWT,8X,4HTWDT//11X,1HF,11X,1HF,11X,1HF,11X,                MSBR 421
     2        1HF,11X,1HF,11X,1HF,11X,1HF//(1X,I3,7E12.4))            MSBR 422
 1040 FORMAT(1H0,2X,1HI,7X,3HVM1,9X,3HVM2,9X,3HVM3,8X,4HVWO1,8X,4HVWO3, MSBR 430
     1 8X,4HPDSC,8X,4HPDTO//32X,6HFT/SEC,33X,7HLB/SQFT//(1X,I3,7F12.4)) MSBR 431
 1041 FORMAT(1H0,2X,1HI,5X,5HRENTC,7X,5HPRNTO,7X,6HRENSO1,6X,6HRENSC2,  MSBR 440
     16X,6HRENSC3,7X,3HHTO,8X,4HAHSO,9X,3HUOA,8X,4HHEAT//77X,         MSBR 441
     2  13HBTU/HR/SQFT/F,13X,6HBTU/HR//(1X,I3,9E12.4))                MSBR 442
 1042 FORMAT(27H0TUBE WALL AVERAGE TEMP. =  ,F10.2)                    4  9
 1043 FORMAT(28H0SHELL SIDE AVERAGE TEMP. =  , F10.2)                  MSBR 460
C                                                                     MSBR 650
```

```
C     READ IN AND PRINT OUT INPUT DATA                                  MSBR 660
      KEY7= 1                                                           MSBR 490
      VM1(1)=0.                                                         MSBR 500
      VM2(1)=0.                                                         MSBR 510
      VM3(1)=0.                                                         MSBR 520
      VWO1(1)=0.                                                        MSBR 530
      VWO3(1)=0.                                                        MSBR 540
      RENSO1(1)=0.                                                      MSBR 550
      RENSO2(1)=0.                                                      MSBR 560
      RENSO3(1)=0.                                                      MSBR 570
      HSO1(1)=0.                                                        MSBR 580
      HSO2(1)=0.                                                        MSBR 590
      HSO3(1)=0.                                                        MSBR 600
C                                                                       MSBR 810
      READ 1001, HEATL, PRDT, PRDS                                      MSBR 620
      READ 1002, CTO, FTO, ETF, ETC                                     MSBR 630
      READ 1003, LK, PLK,WCOND                                          MSBR 640
      READ 1004, RA5, DTR, RA8MAX,KASES,KENTB                           MSBR 650
 1    CONTINUE                                                          MSBR 660
      READ 1005, DIA, WTHK, TRIP,       CUT3, CUT4                      MSBR 670
      HSFCT=1.
      IF(FTO.LT.CTO) HSFCT=-1.
      PRINT 1006, HEATL                                                 MSBR 680
      PRINT 1007, PRDT                                                  MSBR 690
      PRINT 1008, PRDS                                                  MSBR 700
      PRINT 1009, CTO                                                   MSBR 710
      PRINT 1010, FTO                                                   MSBR 720
      PRINT 1011, ETF                                                   MSBR 730
      PRINT 1012, ETC                                                   MSBR 740
      PRINT 1013, LK                                                    MSBR 750
      PRINT 1014, PLK                                                   MSBR 760
      PRINT 1015, WCOND                                                 MSBR 770
      PRINT 1016, RA5                                                   MSBR 780
      PRINT 1017, DTR                                                   MSBR 790
      PRINT 1018, RA8MAX                                                MSBR 800
      PRINT 1019 , KASES                                                MSBR 810
      PRINT 1020, KENTB                                                 MSBR 820
```

```
      PRINT 1021, DIA                                                   MSBR 830
      PRINT 1022, WTHK                                                  MSBR 840
      PRINT 1023, TRIP                                                  MSBR 850
      PRINT 1024, CUT3                                                  MSBR 860
      PRINT 1025, CUT4                                                  MSBR 870
C                                                                       MSB 1650
C     BEGIN GEOMETRY CALCULATIONS FOR SINGLE ANNULUS COUNTER FLOW       MSB 1660
C     DISC AND DOUGHNUT BAFFLED HEAT EXCHANGER                          MSB 1670
      ATUBE =  (3.14159* (DIA**2.0))/4.0                                MSBR 910
      GFTT = 1./3600.                                                   MSBR 920
      GFT = 1./144.                                                     MSBR 930
      DIAI=DIA-2.0*WTHK                                                 MSBR 940
      FATUB  =(3.14159*(DIAI**2.0))/4.0                                 MSBR 950
      KEY1 = 0                                                          MSBR 960
      PERC1 = 0.99                                                      MSBR 970
 2    IF(KEY1.GT.0)BSOI=0.5*(BSL+BSH)                                   MSBR 980
      KEY2 = 0                                                          MSBR 990
      PERC2 = 0.99                                                      MSB 1000
      RA8L=RA5                                                          MSB 1010
      RA8H=RA8MAX                                                       MSB 1020
 3    RA8=0.5*(RA8L  +RA8H  )                                           MSB 1030
      NTO = 4.0*((RA8**2.0)-(RA5**2.0))/(1.12*(TRIP**2.0))              MSB 1040
      RA52=RA5**2                                                       MSB 1050
      RA82=RA8**2                                                       MSB 1060
      RA6=(RA52+CUT4*(RA82-RA52))**.5                                   MSB 1070
      RA7=(RA82-CUT3*(RA82-RA52))**.5                                   MSB 1080
      RA62=RA6**2                                                       MSB 1090
      RA72=RA7**2                                                       MSB 1100
      APO1=3.14159*((RA8)**2.0-(RA7)**2.0)*(1.0-(ATUBE/                 MSB 1110
     1(0.866*((TRIP)**2.0))))                                           MSB 1111
      APO3=3.14159*((RA6)**2.0-(RA5)**2.0)*(1.0-(ATUBE/                 MSB 1120
     1(0.866*(TRIP**2.0))))                                             MSB 1121
      PLAV =  0.955*TRIP                                                MSB 1130
      RB1 = (RA8-RA7)/(1.866*TRIP)                                      MSB 1140
      RB2 = (RA7-RA6)/(0.933*TRIP)                                      MSB 1150
      RB3 = (RA6-RA5)/(1.866*TRIP)                                      MSB 1160
```

```
      LAWO1=3.14159*2.0*RA7*(1.0-(DIA/PLAV))                            MSB 1170
      LAWO3=3.14159*2.0*RA6*(1.0-(DIA/PLAV))                            MSB 1180
      ISUM1 = 4.0*((RA8**2.0)-(RA7**2.0))/(1.12*(TRIP**2.0))            MSB 1190
      SUM1 = ISUM1                                                      MSB 1200
      ISUM2 = 4.0*((RA7**2.0)-(RA6**2.0))/(1.12*(TRIP**2.0))            MSB 1210
      SUM2 = ISUM2                                                      MSB 1220
      ISUM3 = 4.0*((RA6**2.0)-(RA5**2.0))/(1.12*(TRIP**2.0))            MSB 1230
      SUM3 = ISUM3                                                      MSB 1240
      SNT = ISUM1 + ISUM2 + ISUM3                                       MSB 1250
      BSMAX=1.5*((RA8-(RA8-RA7)/2.)-(RA5+(RA6-RA5)/2.))                 MSB 1260
      BSMIN=0.2*(RA8-RA5)                                               MSB 1270
      IF(BSMIN.LT.0.1667)BSMIN=0.1667                                   MSB 1280
      HW=2.*WCOND/(DIA*(ALOG(DIA/DIAI)))                                MSB 1290
      CSPHAV=0.36                                                       MSB 1300
      FSPHAV=0.5571                                                     MSB 1310
      QC=HEATL/(CSPHAV*(CTO-ETC))                                       MSB 1320
      QF=HEATL/(FSPHAV*(FTO-ETF))                                       MSB 1330
      GTO = QF/(NTC*FATUB)                                              MSB 1340
    4 CONTINUE                                                          MSB 1350
      IF(KEY1.EQ.0)BSH=BSMAX                                            MSB 1360
      IF(KEY1.EQ.0)BSL=BSMIN                                            MSB 1370
      IF(KEY1.EQ.0)BSOI=0.5*(BSL+BSH)                                   MSB 1380
      IT = 0                                                            MSB 1390
      KFINAL=0                                                          MSB 1400
    5 I=1                                                               MSB 1410
      TSUM=0.                                                           MSB 1420
      SSUM=0.                                                           MSB 1430
      THEATO = 0.0                                                      MSB 1440
      TPDTO = 0.0                                                       MSB 1450
      TPDSO = 0.0                                                       MSB 1460
      TFO(I)=FTC                                                        MSB 1470
      TCI(I)=CTC                                                        MSB 1480
      KEY4 = 0                                                          MSB 1490
      TIF=-5.0                                                          MSB 1500
      TIC=-5.0                                                          MSB 1510
      CDTF=0.                                                           MSB 1520
      FDTF=0.                                                           MSB 1530
      BSO = BSOI                                                        MSB 1540
```

```
      BRL1 = BSC/((RA8-(RA8-RA7)/2.)-(RA5+(RA6-RA5)/2.))                MSB 1550
      GBRL = 0.77*BRL1**(-.138)                                         MSB 1560
      AWO1 = BSC*LAWC1                                                  MSB 1570
      AWO3 = BSC*LAWC3                                                  MSB 1580
      AW1  = SQRT(AWC1*APO1)                                            MSB 1590
      AW2  = (AWO1+AWO3)/2.                                             MSB 1600
      AW3  = SQRT(AWC3*APO3)                                            MSB 1610
      GSO1 = QC/AW1                                                     MSB 1620
      GSO2 = QC/AW2                                                     MSB 1630
      GSO3 = QC/AW3                                                     MSB 1640
    6 ATC = TCI(I) + (TIC/2.0)                                          MSB 1650
      CFT = ATC +CDTF*HSFCT
      ATF = TFO(I)+TIF/2.                                               MSB 1670
      FFT=ATF-FDTF*HSFCT
      FI=I                                                              MSB 1690
      TUBLN(I) = FI*BSOI                                                MSB 1700
      CVIS=0.2121*EXP(4032./(460.+ATC))                                 MSB 1710
      CVISW=0.2121*EXP(4032./(460.+CFT))                                MSB 1720
      CDEN=141.37-0.02466*ATC                                           MSB 1730
      CCON=0.240                                                        MSB 1740
      CSPH=0.36                                                         MSB 1750
      FVIS=0.062                                                        MSB 1760
      FVISW = 0.062                                                     MSB 1770
      FDEN = 0.7632                                                     MSB 1780
      FCON  = 0.036                                                     MSB 1790
      FSPH = 0.5571                                                     MSB 1800
      VISK = (CVIS/CVISW)**0.14                                         MSB 1810
      FVISK=(FVIS/FVISW)**0.14                                          MSB 1820
      DCVIS = DIA/CVIS                                                  MSB 1830
      CCDEN = 1./CDEN                                                   MSB 1840
      QCCDEN = QC*CCDEN                                                 MSB 1850
C     CALCULATE REYNOLDS AND PRANDTL NUMBER TUBE SIDE                   MSB 2550
      RENTO(I)=DIAI*GTO/FVIS                                            MSB 1870
      PRNTO(I)=FVIS*FSPH/FCON                                           MSB 1880
      HEFI=1.+((RENTO(I)-1000.)/9000.)**0.5                             MSB 1890
      IF(KENTB.NE.1)HEFI=1.                                             MSB 1900
      PDTO(I)=(.0028+.25*RENTO**(-.32))*   BSC*GTO**2*HEFI/             MSB 1910
     1       (DIAI*FDEN*417182400.)                                     MSB 1911
```

```
C       CALCULATE HEAT TRANSFER COEFF TUBE SIDE                          MSB 2640
        HTO(I)=FCCN/CIA*.0217*(RENTO(I)**.8)*(PRNTO(I)**.3333)*FVISK*HEFI MSB 1930
        GO TO 10                                                         MSB 1940
 7      IF(RENTO(I).LT.2100.) GO TO 9                                    MSB 1950
 8      HTO(I) = FCCN/DIA*.089*(RENTO(I)**.6666-125.)*(PRNTO(I)**.3333)*  MSB 1960
       1  FVISK*HEFI*(1.+.3333*(DIAI/TUBLN(I))**.6666)                    MSB 1961
        GO TO 10                                                         MSB 1970
 9      HTO(I) = FCCN/CIA*(4.36+(0.025*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)    MSB 1980
       1  )/(1.+0.0012*RENTO(I)*PRNTO(I)*DIAI/TUBLN(I)))                  MSB 1981
 10     CONTINUE                                                         MSB 1990
C       CALCULATE FLCW AREAS SHELL SIDE                                  MSB 2480
        VWO1(I) =  QCCCEN/AWO1                                           MSB 2010
        VWO3(I) =  QCCCEN/AWO3                                           MSB 2020
        VM1(I) = GSC1*CCDEN                                              MSB 2030
        VM2(I) = GSC2*CCDEN                                              MSB 2040
        VM3(I) = GSC3*CCDEN                                              MSB 2050
C       CALCULATE PRESSURE DRCPS  SHELL SIDE                             MSB 2590
        DP1 = (1.+.6*RB1)*CDEN*VM1(I)**2                                 MSB 2070
        DP2 = .6*RB2*CDEN*VM2(I)**2                                      MSB 2080
        DP3 = (1.+.6*RB3)*CDEN*VM3(I)**2                                 MSB 2090
        RENSO1(I) = GSC1*DCVIS                                           MSB 2100
        RENSO2(I) = GSC2*DCVIS                                           MSB 2110
        RENSO3(I) = GSC3*DCVIS                                           MSB 2120
        HEFO=1.+0.3*((RENSO2(I)-1000.)/9000.)**0.5                       MSB 2130
        IF(KENTB.NE.1)HEFO=1.                                            MSB 2140
        PDSO(I) = (DP1+DP2+DP3)*PLK*HEFO/834624000.                      MSB 2150
C       CALCULATE BJ FACTOR AND SHEL SIDE COEFFICIENT                    MSB 2730
        BJ(1) =(0.346*RENSO1(I)**(-0.382))*GBRL                          MSB 2170
        BJ(2) =(0.346*RENSO2(I)**(-0.382))*GBRL                          MSB 2180
        BJ(3) =(0.346*RENSO3(I)**(-0.382))*GBRL                          MSB 2190
        HSO1(I) = (LK*CSPH*GSC1*BJ(1)*((CCCN/(CSPH*CVIS))**.66))*VISK    MSB 2200
        HSO2(I) = (LK*CSPH*GSC2*BJ(2)*((CCCN/(CSPH*CVIS))**.66))*VISK    MSB 2210
        HSO3(I) = (LK*CSPH*GSC3*BJ(3)*((CCCN/(CSPH*CVIS))**.66))*VISK    MSB 2220
        AHSO(I)=(((HSO1(I)*SUM1)+(HSO2(I)*SUM2)+(HSO3(I)*SUM3))/SNT)*HEFO MSB 2230
        GO TO 12                                                         MSB 2240
 11     CONTINUE                                                         MSB 2250
```

```
12    UOA(I)=1.0/((1.0/AHSO(I))+(1.0/HTO(I))+(1.0/HW))                   MSB 2260
      A = QF*FSPH                                                         MSB 2270
      B = QC*CSPH                                                         MSB 2280
      D = UOA(I)*SNT*BSO    *3.14159*DIA                                  MSB 2290
      P = -HSFCT*(D*(A-B))/(A*B)
      PBAR = EXP(P)                                                       MSB 2310
      C = (B-A)*PBAR                                                      MSB 2320
      TCO(I) = ((TCI(I)*(B*PBAR-A))-(TFO(I)*A*(PBAR-1.)))/C               MSB 2330
      TFI(I) =((TCO(I)-TCI(I))*B/A) + TFO(I)                              MSB 2340
      HEAT(I) =-A*(TFI(I) - TFO(I))                                       MSB 2350
      TWDT(I) = (HEAT(I)/NTO)*ALOG(DIA/DIAI)/(2.0*3.14159*BSO*WCOND)      MSB 2360
      CTIF = TFI(I)-TFO(I)                                                MSB 2370
      CTIC = TCO(I)-TCI(I)                                                MSB 2380
      IF((ABS(CTIF-TIF).LE.(1.5)).AND.(ABS(CTIC-TIC).LE.(1.5)))GO TO 13 MSB 2390
      TIF = CTIF                                                          MSB 2400
      TIC = CTIC                                                          MSB 2410
      GO TO 6                                                             MSB 2420
13    THEATO = THEATO + HEAT(I)                                           MSB 2430
      TPDTO = TPDTO + PDTO(I)                                             MSB 2440
      TPDSO = TPDSO + PDSO(I)                                             MSB 2450
      CDTF=(((HEAT(I))  /NTO)/BSO)/(3.14159*DIA*AHSO(I))                  MSB 3090
      FDTF=CDTF*AHSO(I)  /HTO(I)                                          MSB 3100
      FWT(I)  =ATF-FDTF*HSFCT
      CWT(I)  =ATC+CDTF*HSFCT
      AVWT(I)  =0.5*(FWT(I)  +CWT(I))                                     MSB 3130
      TSUM=TSUM+AVWT(I)                                                   MSB 3140
      SSUM=SSUM+ATC                                                       MSB 2560
      IF(KFINAL.EQ.1.AND.I.EQ.IT) GO TO 15                                MSB 2460
      IF(((ABS(ETF-TFI(I))).LE.((ABS(TFI(I)-TFO(I)))/2.0)).OR.            MSB 2470
     1 (TFI(I).LE.ETF)) GO TO 14                                          MSB 2471
      I=I+1                                                               MSB 2480
      IF(I.GT.129)GO TO 23                                                MSB 2490
      TFO(I) = TFI(I-1)                                                   MSB 2570
      TCI(I) = TCO(I-1)                                                   MSB 2580
      BSO=BSOI                                                            MSB 2590
      GO TO 6                                                             MSB 2600
```

```
 14    KFINAL=1                                                        MSB 2610
       IT=I                                                            MSB 2620
       FIT = IT                                                        MSB 2630
       GO TO 5                                                         MSB 2640
 15    TUBLEN= FIT*BSCI                                                MSB 2650
       TAVT=TSUM/FIT
       SAVT=SSUM/FIT
 16    CONTINUE                                                        MSB 2680
 17    VOL = 0.7854*(DIAI**2.0)*NTO*TUBLEN                             MSB 2690
C      CHECK OF TUBE AND SHELL PRESSURE DROPS                          MSB 3250
       KEY2 = KEY2 + 1                                                 MSB 2710
       IF(PERC2.LE.0.1) GO TO 26                                       MSB 2720
       IF(TPDTO.LT.(PERC2*PRDT)) GO TO 18                              MSB 2730
       IF(TPDTO.GT.PRDT) GO TO 19                                      MSB 2740
       GO TO 20                                                        MSB 2750
 18    IF(RA8.LE.(RA5   +0.005)) GO TO 27                              MSB 2760
       RA8H  =RA8                                                      MSB 2770
       IF(KEY2.NE.30)GO TO 3                                           MSB 2780
       RA8L=RA8L-0.2                                                   MSB 2790
       PERC2 = PERC2 - 0.01                                            MSB 2800
       KEY2=10                                                         MSB 2810
       GO TO 3                                                         MSB 2820
 19    IF(RA8.GE.(RA8MAX-0.005)) GO TO 27                              MSB 2830
       RA8L  =RA8                                                      MSB 2840
       IF(KEY2.NE.30) GO TO 3                                          MSB 2850
       RA8H=RA8H+0.2                                                   MSB 2860
       PERC2 = PERC2 - 0.01                                            MSB 2870
       KEY2=10                                                         MSB 2880
       GO TO 3                                                         MSB 2890
 20    KEY1 = KEY1 + 1                                                 MSB 2900
       IF(PERC1.LE.0.1) GO TO 25                                       MSB 2910
       IF(TPDSO.LT.(PERC1*PRDS)) GO TO 21                              MSB 2920
       IF(TPDSO.GT.PRDS)GO TO 22                                       MSB 2930
       GO TO 28                                                        MSB 2940
 21    IF(BSOI.LE.(BSMIN+0.005))GO TO 24                               MSB 2950
       BSH  =BSOI                                                      MSB 2960
       IF(KEY1.NE.30)GO TO 2                                           MSB 2970
```

```
      BSL=BSL-0.1                                                       MSB 2980
      PERC1 = PERC1 - 0.01                                              MSB 2990
      KEY1=10                                                           MSB 3000
      GO TO 2                                                           MSB 3010
 22   IF(BSOI.GE.(BSMAX-0.005))GO TO 24                                 MSB 3020
      BSL  =BSOI                                                        MSB 3030
      IF(KEY1.NE.30) GO TO 2                                            MSB 3040
      BSH=BSH+0.1                                                       MSB 3050
      PERC1 = PERC1 - 0.01                                              MSB 3060
      KEY1=10                                                           MSB 3070
      GO TO 2                                                           MSB 3080
C                                                                       MSB 3640
C     PRINT EXIT SIGNALS                                                MSB 3650
 23   PRINT 1044,BSO                                                    MSB 3110
 1044 FORMAT(39H1BAFFLE SPACINGS EXCEEDE 129 WITH BSO =,F5.2,2X,4H(FT)) MSB 3120
      GO TO 28                                                          MSB 3130
 24   PRINT 1045                                                        MSB 3140
 1045 FORMAT(20H1BSOI = MAX. OR MIN.)                                   MSB 3150
      GO TO 28                                                          MSB 3160
 25   PRINT 1046                                                        MSB 3170
 1046 FORMAT(48H1 PERC1 FOR SHELL PRESSURE DROP IS LESS THEN 0.1)       MSB 3180
      GO TO 28                                                          MSB 3190
 26   PRINT 1047                                                        MSB 3200
 1047 FORMAT(48H1 PERC2 FOR  TUBE PRESSURE DROP IS LESS THEN 0.1)       MSB 3210
      GO TO 28                                                          MSB 3220
 27   PRINT 1048                                                        MSB 3230
 1048 FORMAT(29H1 SHELL RADIUS = MAX. OR MIN.)                          MSB 3240
      GO TO 28                                                          MSB 3250
C                                                                       MSB 3810
C     END OF CASE, PRINT OUTPUT                                         MSB 3820
 28   DO 29 I = 1,IT                                                    MSB 3280
      V1(I)  = VM1(I)*GFTT                                              MSB 3290
      V2(I)  = VM2(I)*GFTT                                              MSB 3300
      V3(I)  = VM3(I)*GFTT                                              MSB 3310
      VW1(I) = VWO1(I)*GFTT                                             MSB 3320
      VW3(I) = VWO3(I)*GFTT                                             MSB 3330
```

```
 29   CONTINUE                                                          MSB 3340
      TTDSO = TPDSO*GFT                                                 MSB 3350
      TTDTO = TPDTO*GFT                                                 MSB 3360
      TPPERC=TPDTO*100./PRDT                                            MSB 3370
      SPPERC=TPDSO*100./PRDS                                            MSB 3380
      HTPERC=100.*THEATO/HEATL                                          MSB 3390
      AREA=3.14159*DIA*SNT*TUBLEN                                       MSB 3400
C                                                                       MSB 1640
      PRINT 1026,THEATO,HTPERC                                          MSB 3420
      PRINT 1027, QC                                                    MSB 3430
      PRINT 1028, QF                                                    MSB 3440
      PRINT 1029,TTDSO,SPPERC                                           MSB 3450
      PRINT 1030, TTDTO,TPPERC                                          MSB 3460
      PRINT 1031,RA8                                                    MSB 3470
      PRINT 1032,BSOI                                                   MSB 3480
      PRINT 1033,VCL                                                    MSB 3490
      PRINT 1034, AREA                                                  MSB 3500
      PRINT 1035,SNT                                                    MSB 3510
      PRINT 1036,TUBLEN                                                 MSB 3520
      PRINT 1038, GBRL                                                  MSB 3530
      PRINT 1042 ,TAVT                                                  MSB 3540
      PRINT 1043 ,SAVT                                                  MSB 3550
      PRINT 1039, (I,(TCI(I),TCO(I),CWT(I), TFI(I),TFO(I),FWT(I),       MSB 3560
     1       TWCT(I) ),I=1,IT)                                          MSB 3561
      PRINT 1040,(I,(V1(I),V2(I),V3(I),VW1(I),VW3(I),PDSO(I),PDTO(I)),  MSB 3570
     1   I=1,IT)                                                        MSB 3571
      PRINT 1041,(I,(RENTO(I),PRNTO(I),RENSO1(I),RENSO2(I),RENSO3(I),   MSB 3580
     1HTO(I),AHSO(I) ,UOA(I),HEAT(I)),I=1,IT)                           MSB 3581
C                                                                       MSB 4240
C     LOOP FOR ADDITIONAL CASES IF REQUIRED                             MSB 4250
 30   CONTINUE                                                          MSB 3610
      KEY7=KEY7+1                                                       MSB 3620
      IF(KEY7.GT.KASES)GO TO 31                                         MSB 3630
      GO TO 1                                                           MSB 3640
 31   CONTINUE                                                          MSB 3650
      END                                                               MSB 3660
```

Intermediate Variables

The intermediate variable terms used in the RETEX computer program are as defined for the PRIMEX program except for the two terms defined below.

TRIP	Uniform triangular pitch, ft.
PLAV	0.955*TRIP used in calculating the effective cross-flow area between the tubes, ft^2.

Computer Input for Reference MSBR Steam Reheater Exchanger

```
HEAT LOAD REQUIRED =   125CCOCCO.  (BTU/HR)

ALLOWABLE TOTAL TUBE-SIDE PRESSURE DRCP =      4320.  (LB/SQ-FT)

ALLOWABLE TOTAL SHELL-SICE PRESSURE CROP =      8640.  (LB/SQ-FT)

HIGH TEMP. OF SHELL SIDE FLUIC =   1150.00  (F)

HIGH TEMP. OF TUBE SIDE FLUID =    1000.00  (F)

LOW TEMP. OF TUBE SIDE FLUIC =     650.00  (F)

LOW TEMP. OF SHELL SIDE FLUID =    850.00  (F)

HEAT TRANSFER LEAKAGE FACTCR =   0.80000

PRESSURE LEAKAGE FACTOR =   C.5200C

CONDUCTIVITY OF TUBE WALL METAL =   11.6000C  (BTL/HR-FT-F)

INSIDE RADIUS CF OUTER ANNULUS =    C.0      (FEET)

DISTANCE BETWEEN SHELL WALL AND TUBES =    0.04167  (FEET)

MAXIMUM ANTICIPATED OUTER RADIUS OF EXCHANGER =    5.C000C  (FEET)

NUMBER OF CASES RUN =    1

USE OF ENHENCED TUBES =    0  (ONE IF ENHENCEC TUBES ARE USED)

OUTSIDE DIAMETER OF TUBES =    0.0625C  (FEET)

WALL THICKNESS OF TUBES =    C.00292  (FEET)

TRIANGULAR PITCH =    0.C8333  (FEET)

INNER BAFFLE CUT3  =    C.300C0  (PER CENT)

OUTER BAFFLE CUT4  =    C.300C0  (PER CENT)
```

Computer Output for Reference MSBR Steam Reheater Exchanger

```
TOTAL HEAT TRANSFERED =   126488992.  (BTU/HR)  (101.2 PERCENT)

MASS FLOW RATE OF COOLANT =   1157407.  (LB/HR)

MASS FLOW RATE OF FUEL =    641075.  (LB/HR)

SHELL-SIDE TOTAL PRESSURE DROP =      59.52  (LB/SQIN)  ( 99.2 PERCENT)

TUBE-SIDE TOTAL PRESSURE DROP =      29.85  (LB/SQIN)  ( 99.5 PERCENT)

NOMINAL SHELL RADIUS =  0.8838  (FT)

UNIFORM BAFFLE SPACING =  0.7205  (FT)

TUBE FLUID VOLUME CONTAINED IN TUBES =   30.60 (CUBIC FEET)

TOTAL HEAT TRANSFER AREA BASED ON TUBE O.D. =      2376.56  (SQFT)

TOTAL NUMBER OF TUBES =   400.

TOTAL TUBE LENGTH =  30.26  (FT)

BERGLIN MODIFICATION FACTOR =  0.75

TUBE WALL AVERAGE TEMP. =     942.99

SHELL SIDE AVERAGE TEMP. =    1004.44
```

```
  I       TCI          TCC          CWT          TFI          TFO          FWT          TWDT

           F            F            F            F            F            F             F

  1  0.1150E 04   0.1144E 04   0.1103E 04   0.9925E 03   0.1000E 04   0.1090E 04   0.1244E 02
  2  0.1144E 04   0.1137E 04   0.1096E 04   0.9850E 03   0.9925E 03   0.1083E 04   0.1248E 02
  3  0.1137E 04   0.1131E 04   0.1089E 04   0.9775E 03   0.9850E 03   0.1076E 04   0.1255E 02
  4  0.1131E 04   0.1124E 04   0.1082E 04   0.9699E 03   0.9775E 03   0.1069E 04   0.1263E 02
  5  0.1124E 04   0.1118E 04   0.1075E 04   0.9622E 03   0.9699E 03   0.1062E 04   0.1271E 02
  6  0.1118E 04   0.1111E 04   0.1068E 04   0.9545E 03   0.9622E 03   0.1055E 04   0.1279E 02
  7  0.1111E 04   0.1104E 04   0.1061E 04   0.9468E 03   0.9545E 03   0.1048E 04   0.1287E 02
  8  0.1104E 04   0.1098E 04   0.1054E 04   0.9390E 03   0.9468E 03   0.1041E 04   0.1295E 02
  9  0.1098E 04   0.1091E 04   0.1047E 04   0.9311E 03   0.9390E 03   0.1033E 04   0.1302E 02
 10  0.1091E 04   0.1084E 04   0.1040E 04   0.9233E 03   0.9311E 03   0.1026E 04   0.1310E 02
 11  0.1084E 04   0.1077E 04   0.1032E 04   0.9153E 03   0.9233E 03   0.1019E 04   0.1318E 02
 12  0.1077E 04   0.1071E 04   0.1025E 04   0.9073E 03   0.9153E 03   0.1012E 04   0.1326E 02
 13  0.1071E 04   0.1064E 04   0.1018E 04   0.8993E 03   0.9073E 03   0.1004E 04   0.1334E 02
 14  0.1064E 04   0.1057E 04   0.1010E 04   0.8912E 03   0.8993E 03   0.9967E 03   0.1342E 02
 15  0.1057E 04   0.1050E 04   0.1003E 04   0.8831E 03   0.8912E 03   0.9892E 03   0.1350E 02
 16  0.1050E 04   0.1043E 04   0.9956E 03   0.8749E 03   0.8831E 03   0.9817E 03   0.1358E 02
 17  0.1043E 04   0.1036E 04   0.9881E 03   0.8667E 03   0.8749E 03   0.9741E 03   0.1366E 02
 18  0.1036E 04   0.1029E 04   0.9806E 03   0.8585E 03   0.8667E 03   0.9665E 03   0.1374E 02
 19  0.1029E 04   0.1022E 04   0.9730E 03   0.8501E 03   0.8585E 03   0.9589E 03   0.1382E 02
 20  0.1022E 04   0.1014E 04   0.9654E 03   0.8418E 03   0.8501E 03   0.9511E 03   0.1389E 02
 21  0.1014E 04   0.1007E 04   0.9577E 03   0.8334E 03   0.8418E 03   0.9434E 03   0.1397E 02
 22  0.1007E 04   0.9999E 03   0.9500E 03   0.8249E 03   0.8334E 03   0.9356E 03   0.1405E 02
 23  0.9999E 03   0.9926E 03   0.9422E 03   0.8164E 03   0.8249E 03   0.9277E 03   0.1413E 02
 24  0.9926E 03   0.9853E 03   0.9344E 03   0.8079E 03   0.8164E 03   0.9198E 03   0.1421E 02
 25  0.9853E 03   0.9779E 03   0.9265E 03   0.7993E 03   0.8079E 03   0.9119E 03   0.1429E 02
 26  0.9779E 03   0.9705E 03   0.9186E 03   0.7906E 03   0.7993E 03   0.9039E 03   0.1437E 02
 27  0.9705E 03   0.9631E 03   0.9106E 03   0.7819E 03   0.7906E 03   0.8958E 03   0.1445E 02
 28  0.9631E 03   0.9556E 03   0.9026E 03   0.7732E 03   0.7819E 03   0.8877E 03   0.1453E 02
 29  0.9556E 03   0.9480E 03   0.8945E 03   0.7644E 03   0.7732E 03   0.8795E 03   0.1461E 02
 30  0.9480E 03   0.9405E 03   0.8864E 03   0.7555E 03   0.7644E 03   0.8714E 03   0.1469E 02
 31  0.9405E 03   0.9328E 03   0.8782E 03   0.7467E 03   0.7555E 03   0.8631E 03   0.1477E 02
 32  0.9328E 03   0.9252E 03   0.8700E 03   0.7377E 03   0.7467E 03   0.8548E 03   0.1485E 02
 33  0.9252E 03   0.9175E 03   0.8617E 03   0.7287E 03   0.7377E 03   0.8465E 03   0.1493E 02
 34  0.9175E 03   0.9098E 03   0.8527E 03   0.7197E 03   0.7287E 03   0.8373E 03   0.1500E 02
 35  0.9098E 03   0.9020E 03   0.8444E 03   0.7106E 03   0.7197E 03   0.8289E 03   0.1508E 02
 36  0.9020E 03   0.8942E 03   0.8360E 03   0.7015E 03   0.7106E 03   0.8204E 03   0.1515E 02
 37  0.8942E 03   0.8863E 03   0.8275E 03   0.6924E 03   0.7015E 03   0.8118E 03   0.1523E 02
 38  0.8863E 03   0.8784E 03   0.8190E 03   0.6831E 03   0.6924E 03   0.8032E 03   0.1531E 02
 39  0.8784E 03   0.8705E 03   0.8104E 03   0.6739E 03   0.6831E 03   0.7946E 03   0.1539E 02
 40  0.8705E 03   0.8625E 03   0.8018E 03   0.6646E 03   0.6739E 03   0.7859E 03   0.1546E 02
 41  0.8625E 03   0.8545E 03   0.7932E 03   0.6552E 03   0.6646E 03   0.7772E 03   0.1554E 02
 42  0.8545E 03   0.8464E 03   0.7845E 03   0.6458E 03   0.6552E 03   0.7684E 03   0.1561E 02
```

```
 I       VM1        VM2        VM3       VWO1       VWO3       PDSO        PDTO

                              FT/SEC                          LB/SQFT

 1     5.5856     4.7831     6.9035     3.9572     6.0447   210.3354   102.3585
 2     5.5778     4.7764     6.8938     3.9516     6.0362   210.0414   102.3585
 3     5.5700     4.7697     6.8842     3.9461     6.0278   209.7476   102.3585
 4     5.5622     4.7630     6.8745     3.9406     6.0193   209.4527   102.3585
 5     5.5543     4.7563     6.8648     3.9350     6.0108   209.1567   102.3585
 6     5.5465     4.7495     6.8550     3.9294     6.0023   208.8597   102.3585
 7     5.5385     4.7428     6.8453     3.9238     5.9937   208.5619   102.3585
 8     5.5306     4.7360     6.8354     3.9182     5.9851   208.2632   102.3585
 9     5.5226     4.7291     6.8256     3.9125     5.9765   207.9633   102.3585
10     5.5147     4.7223     6.8157     3.9069     5.9679   207.6625   102.3585
11     5.5066     4.7155     6.8058     3.9012     5.9592   207.3607   102.3585
12     5.4986     4.7086     6.7959     3.8955     5.9505   207.0581   102.3585
13     5.4905     4.7017     6.7859     3.8898     5.9418   206.7545   102.3585
14     5.4825     4.6947     6.7759     3.8841     5.9330   206.4502   102.3585
15     5.4744     4.6878     6.7659     3.8783     5.9243   206.1448   102.3585
16     5.4662     4.6808     6.7559     3.8726     5.9155   205.8386   102.3585
17     5.4581     4.6739     6.7458     3.8668     5.9066   205.5315   102.3585
18     5.4499     4.6668     6.7357     3.8610     5.8978   205.2235   102.3585
19     5.4417     4.6598     6.7255     3.8552     5.8889   204.9145   102.3585
20     5.4335     4.6528     6.7154     3.8494     5.8800   204.6047   102.3585
21     5.4252     4.6457     6.7052     3.8435     5.8711   204.2942   102.3585
22     5.4169     4.6386     6.6950     3.8377     5.8621   203.9826   102.3585
23     5.4086     4.6315     6.6847     3.8318     5.8532   203.6705   102.3585
24     5.4003     4.6244     6.6744     3.8259     5.8442   203.3576   102.3585
25     5.3920     4.6173     6.6641     3.8200     5.8351   203.0438   102.3585
26     5.3836     4.6101     6.6538     3.8141     5.8261   202.7291   102.3585
27     5.3753     4.6030     6.6435     3.8081     5.8170   202.4137   102.3585
28     5.3669     4.5958     6.6331     3.8022     5.8080   202.0977   102.3585
29     5.3585     4.5886     6.6227     3.7962     5.7988   201.7808   102.3585
30     5.3500     4.5813     6.6123     3.7903     5.7897   201.4633   102.3585
31     5.3416     4.5741     6.6018     3.7843     5.7806   201.1451   102.3585
32     5.3331     4.5668     6.5914     3.7783     5.7714   200.8261   102.3585
33     5.3246     4.5596     6.5809     3.7723     5.7622   200.5063   102.3585
34     5.3154     4.5517     6.5694     3.7657     5.7522   200.1584   102.3585
35     5.3069     4.5444     6.5589     3.7597     5.7430   199.8376   102.3585
36     5.2983     4.5371     6.5484     3.7536     5.7338   199.5162   102.3585
37     5.2898     4.5297     6.5378     3.7476     5.7245   199.1941   102.3585
38     5.2812     4.5224     6.5272     3.7415     5.7152   198.8715   102.3585
39     5.2726     4.5150     6.5166     3.7354     5.7059   198.5483   102.3585
40     5.2640     4.5077     6.5060     3.7293     5.6966   198.2244   102.3585
41     5.2554     4.5003     6.4953     3.7232     5.6873   197.9001   102.3585
42     5.2468     4.4929     6.4847     3.7171     5.6780   197.5751   102.3585
```

```
  I      RENTO         PRNTC         RENSO1        RENSO2        RENSO3         HTO          AHSO          UOA          HEAT

                                                                                       BTU/HR/SQFT/F                BTU/HR

  1  0.5794E 06   0.9594E 00   0.5449E 05   0.4666E 05   0.6735E 05   0.5026E 03   0.1071E 04   0.3137E 03   0.2673E 07
  2  0.5794E 06   0.9594E 00   0.5395E 05   0.4620E 05   0.6668E 05   0.5026E 03   0.1057E 04   0.3126E 03   0.2682E 07
  3  0.5794E 06   0.9594E 00   0.5340E 05   0.4573E 05   0.6600E 05   0.5026E 03   0.1054E 04   0.3123E 03   0.2698E 07
  4  0.5794E 06   0.9594E 00   0.5285E 05   0.4526E 05   0.6532E 05   0.5026E 03   0.1051E 04   0.3120E 03   0.2715E 07
  5  0.5794E 06   0.9594E 00   0.5230E 05   0.4479E 05   0.6464E 05   0.5026E 03   0.1048E 04   0.3117E 03   0.2732E 07
  6  0.5794E 06   0.9594E 00   0.5175E 05   0.4432E 05   0.6396E 05   0.5026E 03   0.1044E 04   0.3114E 03   0.2748E 07
  7  0.5794E 06   0.9594E 00   0.5120E 05   0.4384E 05   0.6328E 05   0.5026E 03   0.1041E 04   0.3111E 03   0.2765E 07
  8  0.5794E 06   0.9594E 00   0.5064E 05   0.4336E 05   0.6259E 05   0.5026E 03   0.1038E 04   0.3108E 03   0.2782E 07
  9  0.5794E 06   0.9594E 00   0.5008E 05   0.4289E 05   0.6190E 05   0.5026E 03   0.1034E 04   0.3105E 03   0.2799E 07
 10  0.5794E 06   0.9594E 00   0.4952E 05   0.4241E 05   0.6120E 05   0.5026E 03   0.1031E 04   0.3102E 03   0.2816E 07
 11  0.5794E 06   0.9594E 00   0.4896E 05   0.4192E 05   0.6051E 05   0.5026E 03   0.1027E 04   0.3099E 03   0.2833E 07
 12  0.5794E 06   0.9594E 00   0.4839E 05   0.4144E 05   0.5981E 05   0.5026E 03   0.1024E 04   0.3096E 03   0.2850E 07
 13  0.5794E 06   0.9594E 00   0.4783E 05   0.4096E 05   0.5911E 05   0.5026E 03   0.1020E 04   0.3092E 03   0.2867E 07
 14  0.5794E 06   0.9594E 00   0.4726E 05   0.4047E 05   0.5841E 05   0.5026E 03   0.1016E 04   0.3089E 03   0.2884E 07
 15  0.5794E 06   0.9594E 00   0.4669E 05   0.3998E 05   0.5771E 05   0.5026E 03   0.1013E 04   0.3086E 03   0.2901E 07
 16  0.5794E 06   0.9594E 00   0.4612E 05   0.3949E 05   0.5700E 05   0.5026E 03   0.1009E 04   0.3082E 03   0.2918E 07
 17  0.5794E 06   0.9594E 00   0.4555E 05   0.3900E 05   0.5629E 05   0.5026E 03   0.1005E 04   0.3079E 03   0.2935E 07
 18  0.5794E 06   0.9594E 00   0.4497E 05   0.3851E 05   0.5558E 05   0.5026E 03   0.1002E 04   0.3075E 03   0.2952E 07
 19  0.5794E 06   0.9594E 00   0.4440E 05   0.3802E 05   0.5487E 05   0.5026E 03   0.9977E 03   0.3071E 03   0.2969E 07
 20  0.5794E 06   0.9594E 00   0.4382E 05   0.3752E 05   0.5416E 05   0.5026E 03   0.9938E 03   0.3068E 03   0.2986E 07
 21  0.5794E 06   0.9594E 00   0.4324E 05   0.3703E 05   0.5344E 05   0.5026E 03   0.9899E 03   0.3064E 03   0.3003E 07
 22  0.5794E 06   0.9594E 00   0.4266E 05   0.3653E 05   0.5273E 05   0.5026E 03   0.9859E 03   0.3060E 03   0.3020E 07
 23  0.5794E 06   0.9594E 00   0.4208E 05   0.3603E 05   0.5201E 05   0.5026E 03   0.9818E 03   0.3056E 03   0.3038E 07
 24  0.5794E 06   0.9594E 00   0.4150E 05   0.3554E 05   0.5129E 05   0.5026E 03   0.9777E 03   0.3052E 03   0.3054E 07
 25  0.5794E 06   0.9594E 00   0.4092E 05   0.3504E 05   0.5057E 05   0.5026E 03   0.9736E 03   0.3048E 03   0.3072E 07
 26  0.5794E 06   0.9594E 00   0.4033E 05   0.3454E 05   0.4985E 05   0.5026E 03   0.9694E 03   0.3044E 03   0.3089E 07
 27  0.5794E 06   0.9594E 00   0.3975E 05   0.3404E 05   0.4913E 05   0.5026E 03   0.9652E 03   0.3040E 03   0.3106E 07
 28  0.5794E 06   0.9594E 00   0.3916E 05   0.3354E 05   0.4840E 05   0.5026E 03   0.9609E 03   0.3036E 03   0.3123E 07
 29  0.5794E 06   0.9594E 00   0.3858E 05   0.3303E 05   0.4768E 05   0.5026E 03   0.9565E 03   0.3031E 03   0.3140E 07
 30  0.5794E 06   0.9594E 00   0.3799E 05   0.3253E 05   0.4695E 05   0.5026E 03   0.9521E 03   0.3027E 03   0.3157E 07
 31  0.5794E 06   0.9594E 00   0.3740E 05   0.3203E 05   0.4623E 05   0.5026E 03   0.9476E 03   0.3022E 03   0.3174E 07
 32  0.5794E 06   0.9594E 00   0.3682E 05   0.3153E 05   0.4550E 05   0.5026E 03   0.9431E 03   0.3018E 03   0.3191E 07
 33  0.5794E 06   0.9594E 00   0.3623E 05   0.3102E 05   0.4478E 05   0.5026E 03   0.9385E 03   0.3013E 03   0.3208E 07
 34  0.5794E 06   0.9594E 00   0.3559E 05   0.3048E 05   0.4399E 05   0.5026E 03   0.9335E 03   0.3008E 03   0.3224E 07
 35  0.5794E 06   0.9594E 00   0.3501E 05   0.2998E 05   0.4326E 05   0.5026E 03   0.9288E 03   0.3003E 03   0.3241E 07
 36  0.5794E 06   0.9594E 00   0.3442E 05   0.2947E 05   0.4254E 05   0.5026E 03   0.9240E 03   0.2998E 03   0.3257E 07
 37  0.5794E 06   0.9594E 00   0.3383E 05   0.2897E 05   0.4181E 05   0.5026E 03   0.9192E 03   0.2993E 03   0.3274E 07
 38  0.5794E 06   0.9594E 00   0.3325E 05   0.2847E 05   0.4109E 05   0.5026E 03   0.9143E 03   0.2988E 03   0.3290E 07
 39  0.5794E 06   0.9594E 00   0.3266E 05   0.2797E 05   0.4037E 05   0.5026E 03   0.9094E 03   0.2982E 03   0.3307E 07
 40  0.5794E 06   0.9594E 00   0.3208E 05   0.2747E 05   0.3964E 05   0.5026E 03   0.9044E 03   0.2977E 03   0.3323E 07
 41  0.5794E 06   0.9594E 00   0.3149E 05   0.2697E 05   0.3892E 05   0.5026E 03   0.8993E 03   0.2971E 03   0.3339E 07
 42  0.5794E 06   0.9594E 00   0.3091E 05   0.2647E 05   0.3820E 05   0.5026E 03   0.8942E 03   0.2966E 03   0.3356E 07
```

Appendix D

THE SUPEX PROGRAM

The SUPEX computer program is outlined in block-diagram form in Fig. D.1. The input data required for the program are given in Table D.1, and the output received from the computer are given in Table D.2. A complete listing of the main program and its subroutines is followed by definitions of the intermediate variables used in the program and the subroutines and their purposes. To illustrate the use of the SUPEX program, computer print-outs of the input for the MSBR steam generator superheater exchanger discussed in Subsection 4.1 and the output of the SUPEX program are presented.

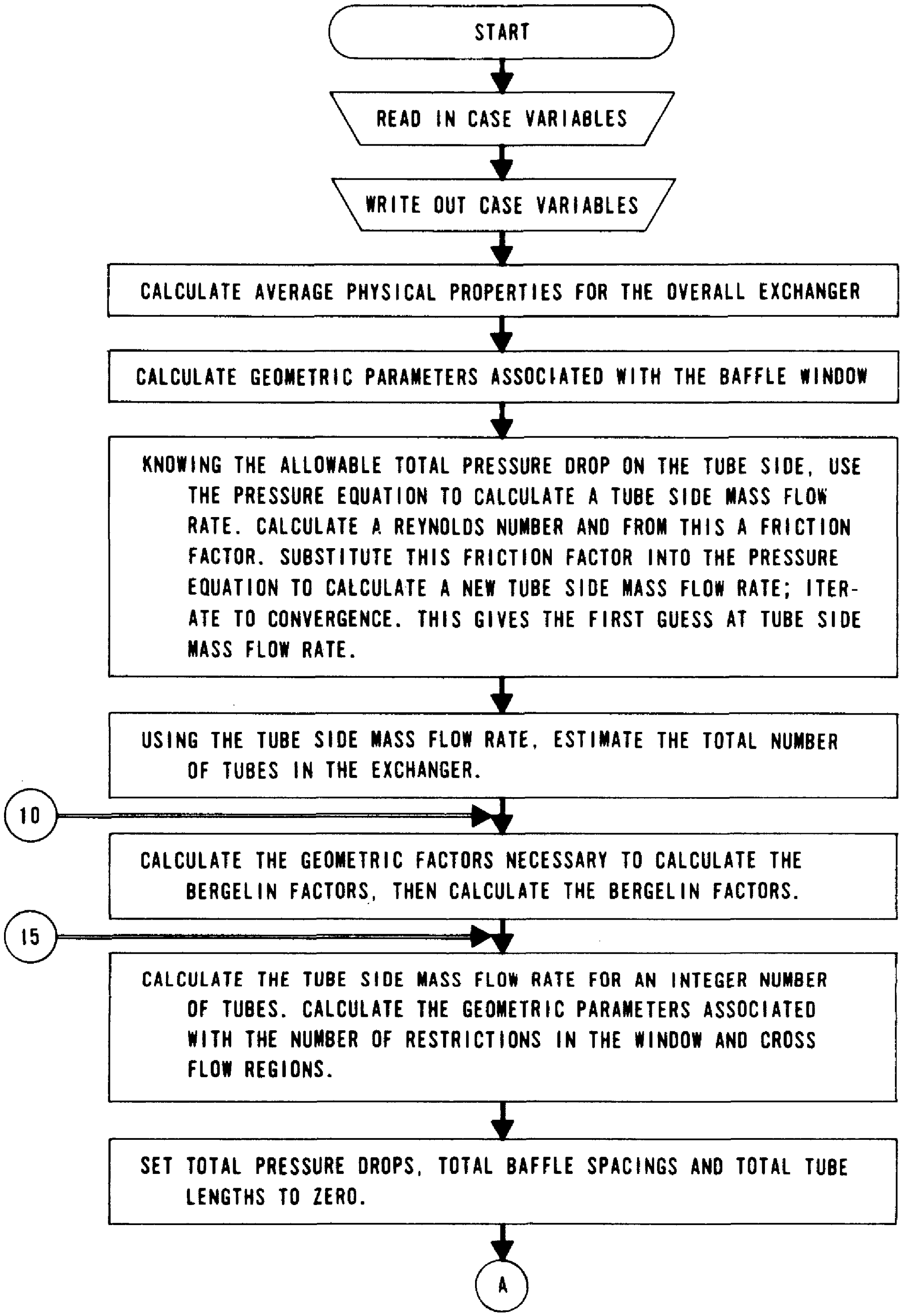

Fig. D.1. Simplified Flow Diagram of the SUPEX Computer Program.

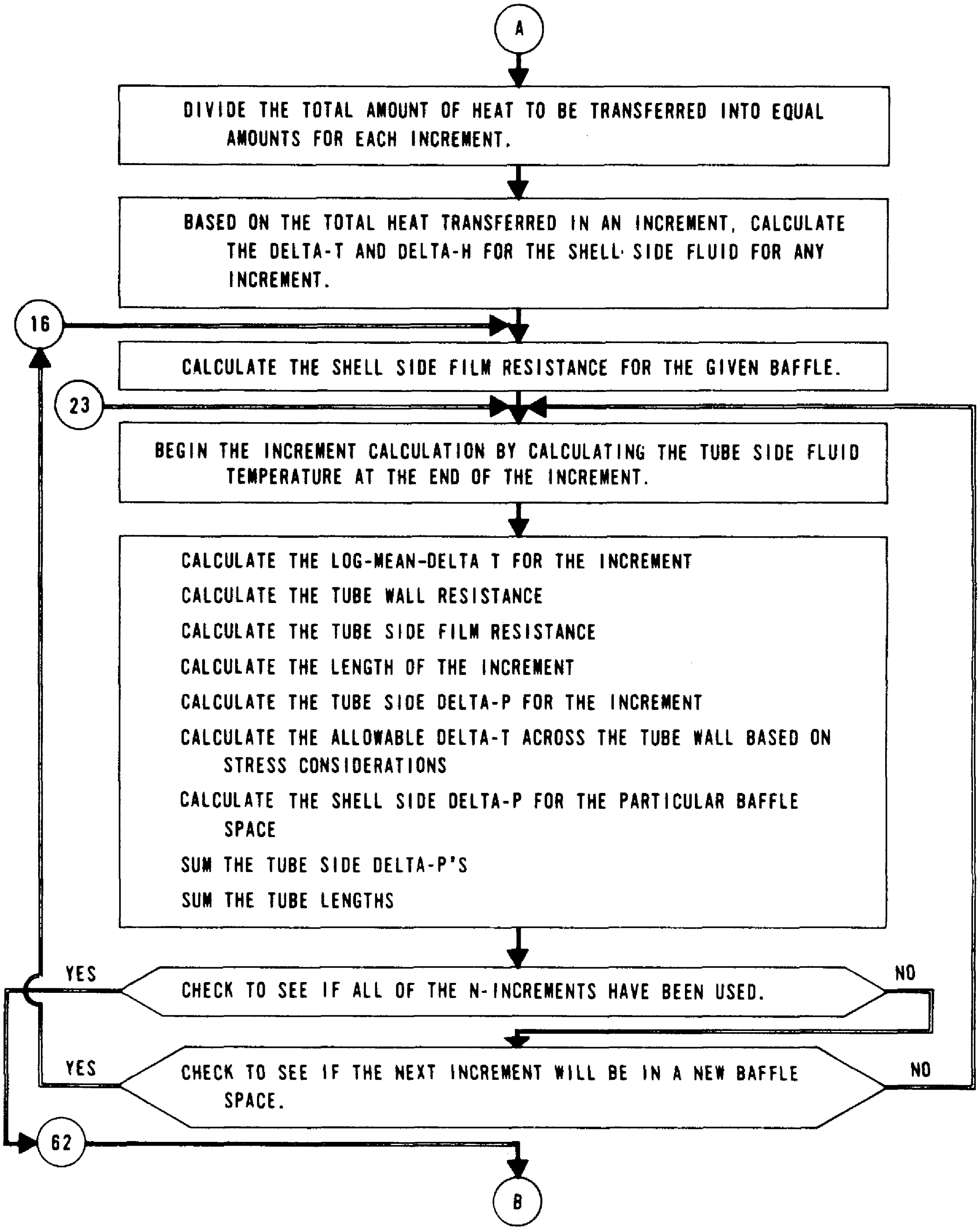

Fig. D.1. (continued)

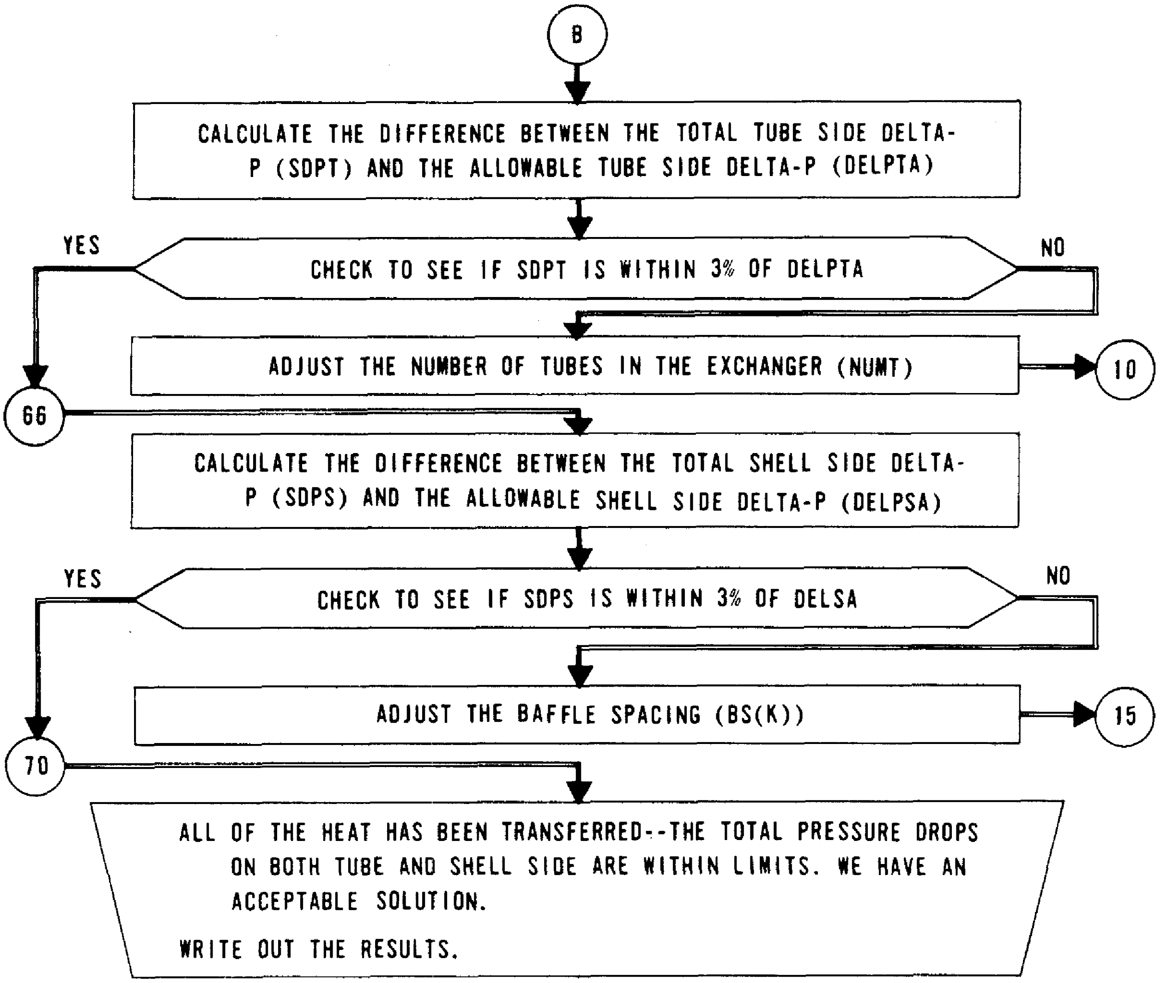

Fig. D.1. (continued)

Table D.1. Computer Input Data for SUPEX Program

Card	Columns	Format	Variable	Term	Units
1	1-10	F10.5	Tube outside diameter	DTO	in.
	11-20	F10.5	Tube wall thickness	THK	in.
	21-30	F10.5	Tube pitch	P	in.
	31-40	I10	Number of increments	N	
2	1-10	F10.1	Salt inlet temperature	TH1	°F
	11-20	F10.1	Salt outlet temperature	TH2	°F
	21-30	F10.1	Steam inlet temperature	TC1	°F
	31-40	F10.1	Steam outlet temperature	TC2	°F
3	1-10	F10.1	Steam inlet pressure	PC1	psi
	11-20	F10.1	Steam exit pressure	PC2	psi
	21-30	F10.1	Allowable total shell-side pressure drop	DELPSA	psi
	31-40	F10.5	Bypass leakage factor for pressure drop	BLFP	
4	1-20	E20.6	Mass flow rate of steam	WC	lb/hr
	21-40	E20.6	Mass flow rate of salt	WH	lb/hr
	41-60	E20.6	Total heat transfer rate	QT	Btu/hr
	61-70	F10.5	Bypass leakage factor for heat transfer	BLFH	
5	1-10	F10.5	Specific heat of salt	CPH	Btu/lb•°F
	11-20	F10.5	Thermal conductivity of salt (hot fluid)	TCH	Btu/ft•hr•°F
	21-30	F10.5	Estimated number of baffle spaces	GNB	
6	1-10	F10.5	Fractional window cut	PW	
	11-20	F10.5	Estimated total tube length	SXG	ft
	21-30	F10.5	Estimated baffle spacing	BSG	ft

Table D.2. Output Data From SUPEX Computer Program

Term	Variable	Units
	For Each Baffle Space	
J	Baffle number	
IBK(J)	Increment number of first increment which lies completely in baffle space J	
DELTW(J)	Calculated temperature drop across tube wall	°F
DELTWA(J)	Allowable temperature drop across tube wall based on allowable stress	°F
TWALL(J)	Temperature of wall material	°F
DELPS(J)	Calculated shell-side pressure drop for the baffle space	psi
DHOT(J)	Mean density of hot fluid (salt) for the baffle space	lb/ft^3
VHOT(J)	Mean viscosity of hot fluid (salt) for the baffle space	lb/ft•hr
	For Each Increment	
I	Increment number	
XI	Tube length for the increment	ft
TH(I)	Temperature of hot fluid (salt)	°F
TC(I)	Temperature of cold fluid (steam)	°F
PC(I)	Pressure of cold fluid (steam)	psi
DELP(I)	Tube pressure drop for the increment	psi
RI(I)	Thermal resistance of inside film for the increment	hr•°F/Btu
RW(I)	Thermal resistance of wall material for the increment	hr•°F/Btu
RO(I)	Thermal resistance of outside film for the baffle space in which the increment lies	hr•°F/Btu
RT(I)	Total thermal resistance between hot and cold fluids for the increment	hr•°F/Btu
	For the Entire Exchanger	
NUMT	Total number of tubes	
NBS	Total number of baffle spaces	
BSL	Length of a baffle space	ft
DS	Inside diameter of exchanger shell	in.

Table D.2 (continued)

Term	Variable	Units
SDPT	Total pressure drop in tubes	psi
SDPS	Total pressure drop in shell	psi
DTLME	Log-mean delta-T	°F
SX	Total tube length	ft
AREAX	Total heat transfer area based on total tube length	ft^2
UEQX	Overall heat transfer coefficient based on total tube length	$Btu/hr \cdot ft^2 \cdot °F$
SBS	Total baffle space length	ft
AREAB	Total heat transfer area based on total baffle space length	ft^2
UEQB	Overall heat transfer coefficient based on total baffle space length	$Btu/hr \cdot ft^2 \cdot °F$

The SUPEX Program Listing

```
**FTN,L,G,E,M.
      PROGRAM SUPEX
      TYPE REAL NEW
      DIMENSION TC(201),TH(201),PC(201),HC(201),
     1DELPS(100),RW(201),RI(201),RO(100),RT(201),U(201),
     2X(201),DELP(201),DELTWA(100),DELTW(100),IBK(100),
     3DHOT(50),VHOT(50),TWALL(50)
      CALL SVH(1,P,T,V,H)
      READINPUTTAPE50,1007,DTO,THK,P,N
      READINPUTTAPE50,1008,TH1,TH2,TC1,TC2
      READINPUTTAPE50,1009,PC1,PC2,DELPSA,BLFP
      READINPUTTAPE50,1010,WC,WH,QT,BLFH
      READINPUTTAPE50,1012,CPH,TCH,GNB
      READINPUTTAPE50,1011,PW,SXG,BSG
      DELPTA=PC1-PC2
      LOP1=0
      LOP2=0
      LOP3=0
      LOP4=0
      LOP5=0
      LOP6=0
      LOP7=0
      LOP8=0
      LOP9=0
      LOP10=0
      LOP11=0
      DELTH=QT/(WH*CPH)
      DTPB=DELTH/GNB
      CALL RITE1(DTO,THK,P,N,TH1,TH2,TC1,TC2,PC1,PC2,DELPTA,DELPSA,WC,
     1   WH,QT,CPH,TCH,PW,BLFP,BLFH,GNB,BSG,SXG)
      BSL = BSG
      DTI=(DTO-2.0*THK)/12.0
      P=P/12.0
      DTO=DTO/12.0
```

```
      TCAV=(TC1+TC2)/2.0                                                SUPE 300
      PCAV=(PC1+PC2)/2.0                                                SUPE 310
      CALL SVH(2,PC1,TC1,SPV1,DUM)                                      SUPE 320
      CALL SVH(2,PC2,TC2,SPV2,DUM)                                      SUPE 330
      CALL SVH(2,PCAV,TCAV,SPVAV,DUM)                                   SUPE 340
      SPVG=(2.0*(SPV1+SPVAV)+SPV2)/5.0                                  SUPE 350
      CALL VISCOS(TC1,PC1,VIS1)                                         SUPE 360
      CALL VISCOS(TC2,PC2,VIS2)                                         SUPE 370
      CALL VISCOS(TCAV,PCAV,VISAV)                                      SUPE 380
      VISG=(2.0*(VIS1+VISAV)+VIS2)/5.0                                  SUPE 390
      CFG=0.014                                                         SUPE 400
      THETAL  =  0.8                                                    SUPE 410
      PERCL  =  (THETAL - 0.5*SINF(2.0*THETAL))/3.14159                 SUPE 420
      THETAU  =  1.5707                                                 SUPE 430
      PERCU =(THETAU  -  0.5*SINF(2.0*THETAU))/3.14159                  SUPE 440
    1 NEW = THETAL + (PW   -PERCL)*(THETAU -THETAL)/(PERCU -PERCL)      SUPE 450
      PNEW = (NEW - 0.5*SINF(2.0*NEW))/3.14159                          SUPE 460
      EPNEW=ABSF(PW-PNEW)                                               SUPE 470
      IF(EPNEW-0.001)4,4,2                                              SUPE 480
    2 THETAL =NEW                                                       SUPE 490
      PERCL = PNEW                                                      SUPE 500
      LOP11=LOP11+1                                                     SUPE 510
      IF(LOP11-10)1,1,3                                                 SUPE 520
    3 WRITEOUTPUTTAPE51,1022,LOP11                                      SUPE 530
      GOTO80                                                            SUPE 540
    4 THETAC = THETAL                                                   SUPE 550
    5 G=3600.0*SQRTF((DELPTA*64.4*144.0*DTI)/(CFG*SXG*SPVG))            SUPE 560
      REG=DTI*G/VISG                                                    SUPE 570
      CFC=(0.00140+(0.125/(REG**0.32)))*4.0                             SUPE 580
      DIFA=ABSF(CFC-CFG)                                                SUPE 590
      IF(DIFA-0.05*CFC)9,9,6                                            SUPE 600
    6 CFG=CFC                                                           SUPE 610
      LOP1=LOP1+1                                                       SUPE 620
      IF(LOP1-10)8,8,7                                                  SUPE 630
    7 WRITEOUTPUTTAPE51,1013,LOP1                                       SUPE 640
      GOTO80                                                            SUPE 650
```

```
8     CONTINUE                                                          SUPE 660
      GOTO5                                                             SUPE 670
9     NUMT=XINTF(WC*4.0/(G*3.1416*DTI**2))                              SUPE 680
10    BNUMT=FLOATF(NUMT)                                                SUPE 690
      LOP10=0                                                           SUPE 700
      DS=P*SQRTF(4.0*BNUMT*0.866/3.1416)                                SUPE 710
      XBAR =  (DS/2.0)*(THETAC - 0.5*SINF(2.0*THETAC)                   SUPE 720
     1    -(2.0*(SINF(THETAC))**3.0)/3.0)/(THETAC-0.5*SINF(2.0*THETAC)) SUPE 721
      BRL1 = BSL / (DS-2.0*XBAR)                                        SUPE 730
      GBRL = 0.77*BRL1**(-0.138)                                        SUPE 740
      AW=PW*3.1416*DS**2/4.0                                            SUPE 750
      AX=(3.1416*DS**2/4.0)-AW                                          SUPE 760
      THETA=(1.50*(3.1416-(4.0*AX/DS**2)))**0.333                       SUPE 770
11    AXC=(3.1416-THETA+(SINF(2.0*THETA)/2.0))*DS**2/4.0                SUPE 780
      DIFB=ABSF(AXC-AX)                                                 SUPE 790
      IF(DIFB-0.02*AX)15,15,12                                          SUPE 800
12    THETA2=(1.50*(3.1416-(4.0*AXC/DS**2)))**0.333                     SUPE 810
      AXC2=(3.1416-THETA2+(SINF(2.0*THETA2)/2.0))*DS**2/4.0             SUPE 820
      THETA=(AX-AXC)*(THETA2-THETA)/(AXC2-AXC)+THETA                    SUPE 830
      LOP2=LOP2+1                                                       SUPE 840
      IF(LOP2-10)14,14,13                                               SUPE 850
13    WRITEOUTPUTTAPE51,1014,LOP2                                       SUPE 860
      GOTO80                                                            SUPE 870
14    CONTINUE                                                          SUPE 880
      GOTO11                                                            SUPE 890
15    GC=4.0*WC/(BNUMT*3.1416*DTI**2)                                   SUPE 900
      XB=DS*COSF(THETA)/2.0                                             SUPE 910
      CNB=2.0*XB/(0.866*P)                                              SUPE 920
      XH=(DS/2.0)-XB                                                    SUPE 930
      CNW=(XH/(0.866*P))-1.0                                            SUPE 940
      XC=DS*SINF(THETA)                                                 SUPE 950
      PCFB=(P-DTO)/P                                                    SUPE 960
      SBK=PCFB*(DS+XC)/2.0                                              SUPE 970
      SW=PW*BNUMT*(0.866*P**2-(3.1416*DTO**2/4.0))                      SUPE 980
      SDPT=0.0                                                          SUPE 990
      SDPS=0.0                                                          SUP 1000
      LOP8=0                                                            SUP 1010
```

```
      MS=1                                                              SUP 1020
      SX=0                                                              SUP 1030
      SBS=0                                                             SUP 1040
      TC(1)=TC2                                                         SUP 1050
      TH(1)=TH1                                                         SUP 1060
      RWK=DTO*LOGF(DTO/DTI)/2.0                                         SUP 1070
      PC(1)=PC2                                                         SUP 1080
      CALL SVH(2,PC2,TC2,DUM,HC(1))                                     SUP 1090
      BN=FLOATF(N)                                                      SUP 1100
      QX=QT/BN                                                          SUP 1110
      DECT=QX/(WH*CPH)                                                  SUP 1120
      DECH=QX/WC                                                        SUP 1130
      I=1                                                               SUP 1140
      K=1                                                               SUP 1150
   16 SB = SBK*BSL                                                      SUP 1160
      LOP7=0                                                            SUP 1170
      TCON=TH(I)-DTPB/2.0                                               SUP 1180
      DENH=141.38E+00-2.466E-02*TCON                                    SUP 1190
      VISH=0.2122E+00*EXPF(4032.0E+00/(TCON+460.0E+00))                 SUP 1200
      DHOT(K)=DENH                                                      SUP 1210
      VHOT(K)=VISH                                                      SUP 1220
      CON1=(CPH*VISH/TCH)**0.667E+00                                    SUP 1230
      GM=WH/SB                                                          SUP 1240
      RECB=DTO*GM/VISH                                                  SUP 1250
      IF(RECB-800.0)17,18,18                                            SUP 1260
   17 HJB=0.571/(RECB**0.456)                                           SUP 1270
      GOTO19                                                            SUP 1280
   18 HJB=0.346/(RECB**0.382)                                           SUP 1290
   19 HB=HJB*CPH*GM/CON1                                                SUP 1300
      GW=WH/SW                                                          SUP 1310
      GS=SQRTF(GM*GW)                                                   SUP 1320
      RECW=DTO*GS/VISH                                                  SUP 1330
      IF(RECW-800.0)20,21,21                                            SUP 1340
   20 HJW=0.571/(RECW**0.456)                                           SUP 1350
      GOTO22                                                            SUP 1360
   21 HJW=0.346/(RECW**0.382)                                           SUP 1370
```

```
22    HW=HJW*CPH*GS/CON1                                                SUP 1380
      HO=(HB*(1.0-2.0*PW)+HW*(2.0*PW))*BLFH                             SUP 1390
      HO = HO*GBRL                                                      SUP 1400
      RO(K)=1.0/HO                                                      SUP 1410
23    TH(I+1)=TH(I)-DECT                                                SUP 1420
      LOP5=0                                                            SUP 1430
      HC(I+1)=HC(I)-DECH                                                SUP 1440
      DELPP=0.0                                                         SUP 1450
24    PC(I+1)=PC(I)+DELPP                                               SUP 1460
      LOP3=0                                                            SUP 1470
      LOP4=0                                                            SUP 1480
      TC(I+1)=TC(I)-DECH                                                SUP 1490
25    CALL SVH(2,PC(I+1),TC(I+1),DUM,HCG)                               SUP 1500
      EH=ABSF(HC(I+1)-HCG)                                              SUP 1510
      IF(EH-0.001*HC(I+1))31,31,26                                      SUP 1520
26    TRIAL=TC(I+1)                                                     SUP 1530
      HRIAL=HCG                                                         SUP 1540
      TC(I+1)=TC(I+1)+(HC(I+1)-HCG)*(TC(I)-TC(I+1))/(HC(I)-HCG)         SUP 1550
27    CALLSVH(2,PC(I+1),TC(I+1),DUM,HCG)                                SUP 1560
      EH=ABSF(HC(I+1)-HCG)                                              SUP 1570
      IF(EH-0.001*HC(I+1))31,31,28                                      SUP 1580
28    TNEXT=TC(I+1)+(HC(I+1)-HCG)*(TC(I+1)-TRIAL)/(HCG-HRIAL)           SUP 1590
      TRIAL=TC(I+1)                                                     SUP 1600
      HRIAL=HCG                                                         SUP 1610
      TC(I+1)=TNEXT                                                     SUP 1620
      LOP3=LOP3+1                                                       SUP 1630
      IF(LOP3-10)30,30,29                                               SUP 1640
29    WRITEOUTPUTTAPE51,1015,LOP3                                       SUP 1650
      GOTO80                                                            SUP 1660
30    GOTO27                                                            SUP 1670
31    DENOM=(TH(I+1)-TC(I+1))/(TH(I)-TC(I))                             SUP 1680
      TDEN=ABSF(DENOM-1.0)                                              SUP 1690
      IF(TDEN-0.05) 32,33,33                                            SUP 1700
32    DELTLM=0.5E+00*(TH(I+1)-TC(I+1)+TH(I)-TC(I))                      SUP 1710
      GO TO 34                                                          SUP 1720
33    DELTLM=(TH(I+1)-TC(I+1)-TH(I)+TC(I))/LOGF((TH(I+1)-TC(I+1))/(TH(I)SUP 1730
     1-TC(I)))                                                          SUP 1731
```

```
34    CONTINUE
      TM=(TC(I+1)+TC(I))/2.0
      PM=(PC(I+1)+PC(I))/2.0
      CALL SVH(2,PM,TM,SPVB,HFB)
      PM=(PC(I+1)+PC(I))/2.0
      CALL VISCOS(TM,PM,VISB)
      TW=TM+0.23*DELTLM
      TCW=0.006375*TW+4.06
      RW(I)=RWK/TCW
      DTFM=0.1*DELTLM
35    TMS=TM+DTFM
      CALL SVH(2,PM,TMS,SPVI,HFI)
      CALLCONDT(TMS,PM,TCFI)
      CALL VISCOS(TMS,PM,VISFI)
      CRE=(DTI*GC/VISFI)**0.923
      CPR=(((HFI-HFB)/(TMS-TM))*(VISFI/TCFI))**0.613
      CSV=(SPVB/SPVI)**0.231
      HI=0.00459*(TCFI/DTI)*CRE*CPR*CSV
      RI(I)=DTO/(HI*DTI)
      RT(I)=RO(K)+RW(I)+RI(I)
      DTFMC=RI(I)*DELTLM/RT(I)
      IF(ABSF(DTFM-DTFMC)-0.03*DTFMC)39,39,36
36    DTFM2=(DTFM+DTFMC)*.5
      TMS2=TM+DTFM2
      CALL SVH(2,PM,TMS2,SPVI2,HFI2)
      CALL CONDT(TMS2,PM,TCFI2)
      CALL VISCOS(TMS2,PM,VISFI2)
      CRE2=(DTI*GC/VISFI2)**0.923
      CPR2=(((HFI2-HFB)/(TMS2-TM))*(VISFI2/TCFI2))**0.613
      CSV2=(SPVB/SPVI2)**0.231
      H2I=0.00459*TCFI2*CRE2*CPR2*CSV2/DTI
      R2I=CTO/(H2I*DTI)
      R2T=RO(K)+RW(I)+R2I
      DTFMC2=R2I*DELTLM/R2T
      SLOPE=(DTFMC-DTFMC2)/(DTFM-DTFM2)
      DTFM=(DTFMC-(SLOPE*DTFM))/(1.0-SLOPE)
```

```
      LOP4=LOP4+1                                                       SUP 2100
      IF(LOP4-10)38,38,37                                               SUP 2110
 37   WRITEOUTPUTTAPE51,1016,LOP4                                       SUP 2120
      GOTO80                                                            SUP 2130
 38   CONTINUE                                                          SUP 2140
      GOTO35                                                            SUP 2150
 39   U(I)=1.0/RT(I)                                                    SUP 2160
      X(I)=QX/(BNUMT*3.1416*DTO*U(I)*DELTLM)                            SUP 2170
      RE=DTI*GC/VISB                                                    SUP 2180
      CFI=0.00140+0.125/(RE**0.32)                                      SUP 2190
      DELP(I)=(4.0*CFI*X(I)/DTI)*GC**2.0*SPVB/(64.4*3600.**2.*144.0)    SUP 2200
      DIFC=ABSF(DELP(I)-DELPP)                                          SUP 2210
      IF(DIFC-0.05*DELP(I))43,43,40                                     SUP 2220
 40   DELPP=DELP(I)                                                     SUP 2230
      LOP5=LOP5+1                                                       SUP 2240
      IF(LOP5-10)42,42,41                                               SUP 2250
 41   WRITEOUTPUTTAPE51,1017,LOP5                                       SUP 2260
      GOTO80                                                            SUP 2270
 42   CONTINUE                                                          SUP 2280
      GOTO24                                                            SUP 2290
 43   IF(MS)53,53,44                                                    SUP 2300
 44   IBK(K)=I                                                          SUP 2310
      TW=(RI(I)+0.5*RW(I))*(TH(I)-TC(I))/RT(I)+TC(I)                    SUP 2320
      ALPHA=(0.0031*TW+5.91)                                            SUP 2330
      ETW=31.65-0.005*TW                                                SUP 2340
      CON2=ALPHA*ETW/(1.4*LOGF(DTO/DTI))                                SUP 2350
      CON3=1.0-(2.0*DTO**2*LOGF(DTO/DTI)/(DTO**2-DTI**2))               SUP 2360
      CON3=CON3*(-1.)                                                   SUP 2370
      IF(TW-1015.3)45,46,46                                             SUP 2380
 45   B=24000.0                                                         SUP 2390
      SL=7.5                                                            SUP 2400
      GOTO47                                                            SUP 2410
 46   B=57000.0                                                         SUP 2420
      SL=40.0                                                           SUP 2430
 47   CON4=3.0*(B-SL*TW)-26000.0                                        SUP 2440
      TWALL(K)=TW                                                       SUP 2450
      DELTWA(K)=CON4/(CON2*CON3)                                        SUP 2460
      DELTW(K)=RW(I)*(TH(I)-TC(I))/RT(I)                                SUP 2470
```

```
48     IF(I-1)51,51,49                                                  SUP 2480
49     IF(N-I)51,51,50                                                  SUP 2490
50     BWN=1.0                                                          SUP 2500
       GOTO52                                                           SUP 2510
51     BWN=0.5                                                          SUP 2520
52     DELPSB=0.6*CNB*(GM/3600.0)**2/(64.4*144.0*DENH)                  SUP 2530
       DELPSW=BWN*(2.0+0.6*CNW)*(GS/3600.0)**2/(64.4*144.0*DENH)        SUP 2540
       DELPS(K)=(DELPSB+DELPSW)*BLFP                                    SUP 2550
       SDPS=SDPS+DELPS(K)                                               SUP 2560
       SBS = SBS+BSL                                                    SUP 2570
53     SDPT=SDPT+DELP(I)                                                SUP 2580
       SX=SX+X(I)                                                       SUP 2590
       IF(N-I)62,62,54                                                  SUP 2600
54     I=I+1                                                            SUP 2610
       IF(SBS-SX)58,58,55                                               SUP 2620
55     MS=0                                                             SUP 2630
       LOP7=LOP7+1                                                      SUP 2640
       IF(LOP7-30)57,57,56                                              SUP 2650
56     WRITEOUTPUTTAPE51,1018,LOP7                                      SUP 2660
       GOTO80                                                           SUP 2670
57     CONTINUE                                                         SUP 2680
       GOTO23                                                           SUP 2690
58     MS=1                                                             SUP 2700
       K=K+1                                                            SUP 2710
59     CONTINUE                                                         SUP 2720
       LOP8=LOP8+1                                                      SUP 2730
       IF(LOP8-30)61,61,60                                              SUP 2740
60     WRITEOUTPUTTAPE51,1019,LOP8                                      SUP 2750
       GOTO80                                                           SUP 2760
61     CONTINUE                                                         SUP 2770
       GOTO16                                                           SUP 2780
62     EDPT=ABSF(SDPT-DELPTA)                                           SUP 2790
       IF(EDPT-0.03*DELPTA)66,66,63                                     SUP 2800
63     NUMT=XINTF(BNUMT*(SDPT/DELPTA)**0.35)                            SUP 2810
       LOP9=LOP9+1                                                      SUP 2820
       IF(LOP9-10)65,65,64                                              SUP 2830
64     WRITEOUTPUTTAPE51,1020,LOP9                                      SUP 2840
       GOTO80                                                           SUP 2850
```

```
65    CONTINUE
      BSG=BSL
      GOTO10
66    EDPS = ABSF(SDPS - DELPSA)
      IF(EDPS - 0.03*DELPSA)70,70,67
67    BSL = BSL*SQRTF(SDPS/DELPSA)
      LOP10=LOP10+1
      IF(LOP10-10)69,69,68
68    WRITEOUTPUTTAPE51,1021,LOP10
      GOTO80
69    CONTINUE
      GOTO15
70    CONTINUE
      CALL RITE2
      J=0
71    JN=J+1
      JNC=49+JN
      IF(JN.GT.K) GO TO 73
      WRITEOUTPUTTAPE51,1001
1001  FORMAT(1H1,//,3X,1HJ,5X,5H1ST-I,4X,6HDELT-W,3X,8HDELT-W-A,3X,
     1  6HT-WALL,3X,6HDELP-S,3X,6HDENS-H,3X,6HVISC-H)
      WRITEOUTPUTTAPE51,1002
1002  FORMAT(1H ,4(1H-),3X,6(1H-),3X,7(1H-),3X,8(1H-),4(3X,6(1H-)),/)
      NBS = K
      DO 72 J=JN,K,1
      WRITEOUTPUTTAPE51,1003,J,IBK(J),DELTW(J),DELTWA(J),TWALL(J),
     1   DELPS(J),DHOT(J),VHOT(J)
1003  FORMAT(I5,3X,I6,3X,F7.2,3X,F8.2,2(3X,F6.1,3X,F6.3))
      IF(J.EQ.JNC) GO TO 71
72    CONTINUE
73    CONTINUE
      CALL RITE3
      I=0
74    IN=I+1
      INC=49+IN
      IF(IN.GT.N) GO TO 76
      WRITEOUTPUTTAPE51,1004
```

```
1004 FORMAT(1H1,//,3X,1HI,5X,6HLENGTH,4X,5HT-HOT,5X,6HT-COLD,4X,         SUP 3210
    1  6HP-COLD,4X,6HDELP-C,4X,6HRES-IN,4X,8HRES-WALL,4X,7HRES-OUT,     SUP 3211
    2  4X,7HRES-TOT)                                                    SUP 3212
     WRITEOUTPUTTAPE51,1005                                             SUP 3220
1005 FORMAT(1H ,5(1H-),3X,6(1H-),3X,2(7(1H-),3X),8(1H-),3X,6(1H-),      SUP 3230
    1  4(3X,8(1H-)),/)                                                  SUP 3231
     DO 75 I=IN,N,1                                                     SUP 3240
     RO(I)=RT(I)-RI(I)-RW(I)                                            SUP 3250
     WRITEOUTPUTTAPE51,1006,I,X(I),TH(I),TC(I),PC(I),DELP(I),RI(I),     SUP 3260
    1   RW(I),RO(I),RT(I)                                               SUP 3261
1006 FORMAT(I6,3X,F6.3,3X,2(F7.1,3X),F8.1,3X,F6.3,4(3X,F8.6))           SUP 3270
     IF(I.EQ.INC) GO TO 74                                              SUP 3280
75   CONTINUE                                                           SUP 3290
76   CONTINUE                                                           SUP 3300
     AREAX=BNUMT*SX*3.1416*DTO                                          SUP 3310
     DENOM=(TH1-TC2)/(TH2-TC1)                                          SUP 3320
     TDEN=ABSF(DENOM-1.0)                                               SUP 3330
     IF(TDEN-0.05) 77,78,78                                             SUP 3340
77   DTLME=0.5E+00*(TH1-TC2+TH2-TC1)                                    SUP 3350
     GO TO 79                                                           SUP 3360
78   CONTINUE                                                           SUP 3370
     DTLME=(TH1-TC2-TH2+TC1)/LOGF((TH1-TC2)/(TH2-TC1))                  SUP 3380
79   CONTINUE                                                           SUP 3390
     UEQX=QT/(AREAX*DTLME)                                              SUP 3400
     AREAB=AREAX*SBS/SX                                                 SUP 3410
     UEQB=QT/(AREAB*DTLME)                                              SUP 3420
     DS=DS*12.0                                                         SUP 3430
     CALL RITE4(NUMT,DS,SDPT,SCPS,DTLME,SX,AREAX,UEQX,SBS,AREAB,UEQB,   SUP 3440
    1   NBS,BSL)                                                        SUP 3441
80   CONTINUE                                                           SUP 3450
     CALLEXIT                                                           SUP 3460
1007 FORMAT(F10.5,F10.5,F10.5,I10)                                      SUP 3470
1008 FORMAT(4F10.1)                                                     SUP 3480
1009 FORMAT(F10.1,F10.1,F10.1,F10.5)                                    SUP 3490
1010 FORMAT(E20.6,E20.6,E20.6,F10.5)                                    SUP 3500
1011 FORMAT(3F10.5)                                                     SUP 3510
1012 FORMAT(3F10.5)                                                     SUP 3520
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1013 FORMAT(8H LOP 1 =I4)                                               SUP 3530
1014 FORMAT(8H LOP 2 =I4)                                               SUP 3540
1015 FORMAT(8H LOP 3 =I4)                                               SUP 3550
1016 FORMAT(8H LOP 4 =I4)                                               SUP 3560
1017 FORMAT(8H LOP 5 =I4)                                               SUP 3570
1018 FORMAT(8H LOP 7 =I4)                                               SUP 3580
1019 FORMAT(8H LOP 8 =I4)                                               SUP 3590
1020 FORMAT(8H LOP 9 =I4)                                               SUP 3600
1021 FORMAT(9H LOP 10 =I4)                                              SUP 3610
1022 FORMAT(9H LOP 11 =I4)                                              SUP 3620
     END                                                                SUP 3630
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      SUBROUTINE RITE1(DTO,THK,P,N,TH1,TH2,TC1,TC2,PC1,PC2,DELPTA,      RITE1 10
     1   DELPSA,WC,WH,QT,CPH,TCH,PW,BLFP,BLFH,GNB,BSG,SXG)              RITE1 11
      WRITEOUTPUTTAPE51,1001                                            RITE1 20
      WRITEOUTPUTTAPE51,1002,DTC                                        RITE1 30
      WRITEOUTPUTTAPE51,1003,THK                                        RITE1 40
      WRITEOUTPUTTAPE51,1004,P                                          RITE1 50
      WRITEOUTPUTTAPE51,1005,N                                          RITE1 60
      WRITEOUTPUTTAPE51,1006,TH1                                        RITE1 70
      WRITEOUTPUTTAPE51,1007,TH2                                        RITE1 80
      WRITEOUTPUTTAPE51,1008,TC1                                        RITE1 90
      WRITEOUTPUTTAPE51,1009,TC2                                        RITE 100
      WRITEOUTPUTTAPE51,1010,PC2                                        RITE 110
      WRITEOUTPUTTAPE51,1011,DELPTA                                     RITE 120
      WRITEOUTPUTTAPE51,1012,DELPSA                                     RITE 130
      WRITEOUTPUTTAPE51,1013,WC                                         RITE 140
      WRITEOUTPUTTAPE51,1014,WH                                         RITE 150
      WRITEOUTPUTTAPE51,1015,QT                                         RITE 160
      WRITEOUTPUTTAPE51,1016,CPH                                        RITE 170
      WRITEOUTPUTTAPE51,1017,TCH                                        RITE 180
      WRITEOUTPUTTAPE51,1018,PW                                         RITE 190
      WRITEOUTPUTTAPE51,1019,BLFP                                       RITE 200
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      WRITEOUTPUTTAPE51,1020,BLFH                                       RITE 210
      NBSR = IFIX(GNB)                                                  RITE 220
      WRITEOUTPUTTAPE51,1021,NBSR                                       RITE 230
      WRITEOUTPUTTAPE51,1022,BSG                                        RITE 240
      WRITEOUTPUTTAPE51,1023,SXG                                        RITE 250
      RETURN                                                            RITE 260
 1001 FORMAT(1H1,//,24X,69H* * *  THE FOLLOWING IS THE INPUT INFORMATIONRITE 270
     1 FOR THIS PROBLEM  * * *,///)                                     RITE 271
 1002 FORMAT(1H ,36HOUTSIDE DIAMETER OF TUBES (INCHES)= ,F6.3)          RITE 280
 1003 FORMAT(1H0,30HTUBE WALL THICKNESS (INCHES)= ,F7.4)                RITE 290
 1004 FORMAT(1H0,21HTUBE PITCH (INCHES)= ,F7.4)                         RITE 300
 1005 FORMAT(1H0,58HNUMBER OF INCREMENTS INTO WHICH THE EXCHANGER IS DIVRITE 310
     1IDED= ,I4,//)                                                     RITE 311
 1006 FORMAT(1H0,36HINLET TEMPERATURE OF HOT FLUID (F)= ,F7.1)          RITE 320
 1007 FORMAT(1H0,37HOUTLET TEMPERATURE OF HOT FLUID (F)= ,F7.1)         RITE 330
 1008 FORMAT(1H0,37HINLET TEMPERATURE OF COLD FLUID (F)= ,F7.1)         RITE 340
 1009 FORMAT(1H0,38HOUTLET TEMPERATURE OF COLD FLUID (F)= ,F7.1,//)     RITE 350
 1010 FORMAT(1H0,37HOUTLET PRESSURE OF COLD FLUID (PSI)= ,F7.1)         RITE 360
 1011 FORMAT(1H0,50HALLOWABLE TOTAL PRESSURE DROP ON TUBE SIDE (PSI)= , RITE 370
     1  F7.1)                                                           RITE 371
 1012 FORMAT(1H0,51HALLOWABLE TOTAL PRESSURE DROP ON SHELL SIDE (PSI)= ,RITE 380
     1  F7.1,//)                                                        RITE 381
 1013 FORMAT(1H0,38HMASS FLOW RATE OF COLD FLUID (LB/HR)= ,1PE10.3)     RITE 390
 1014 FORMAT(1H0,37HMASS FLOW RATE OF HOT FLUID (LB/HR)= ,1PE10.3)      RITE 400
 1015 FORMAT(1H0,35HTOTAL HEAT TRANSFER RATE (BTU/HR)= ,1PE10.3)        RITE 410
 1016 FORMAT(1H0,39HSPECIFIC HEAT OF HOT FLUID (BTU/LB-F)= ,F6.3)       RITE 420
 1017 FORMAT(1H0,49HTHERMAL CONDUCTIVITY OF HOT FLUID (BTU/HR-FT-F)= ,  RITE 430
     1  F6.3)                                                           RITE 431
 1018 FORMAT(1H0,23HFRACTIONAL WINDOW CUT= ,F5.2,//)                    RITE 440
 1019 FORMAT(1H0,37HBY-PASS LEAKAGE FACTOR FOR PRESSURE= ,F6.3)         RITE 450
 1020 FORMAT(1H0,42HBY-PASS LEAKAGE FACTOR FOR HEAT TRANSFER= ,F6.3,//) RITE 460
 1021 FORMAT(1H0,50HESTIMATE OF THE NUMBER OF BAFFLE SPACES REQUIRED= , RITE 470
     1   I3)                                                            RITE 471
 1022 FORMAT(1H0,46HESTIMATE OF THE LENGTH OF A BAFFLE SPACE(FT)= ,F5.2)RITE 480
 1023 FORMAT(1H0,39HESTIMATE OF THE TOTAL TUBE LENGTH(FT)= ,F6.2)       RITE 490
      END                                                               RITE 500
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      SUBROUTINE RITE2                                                 RITE2 10
      WRITEOUTPUTTAPE51,1001                                           RITE2 20
      WRITEOUTPUTTAPE51,1002                                           RITE2 30
      WRITEOUTPUTTAPE51,1003                                           RITE2 40
      WRITEOUTPUTTAPE51,1004                                           RITE2 50
      WRITEOUTPUTTAPE51,1005                                           RITE2 60
      WRITEOUTPUTTAPE51,1006                                           RITE2 70
      WRITEOUTPUTTAPE51,1007                                           RITE2 80
      WRITEOUTPUTTAPE51,1008                                           RITE2 90
      WRITEOUTPUTTAPE51,1009                                           RITE 100
      RETURN                                                           RITE 110
1001 FORMAT(1H1,//,12X,95H* * *  THE FOLLOWING TABLE GIVES INFORMATION RITE 120
     1FOR EACH BAFFLE SPACE THROUGH THE EXCHANGER  * * *,//,35X,50HTHE CRITE 121
     2OLUMN LABELS FOR THIS TABLE ARE DEFINED BELOW,////)              RITE 122
1002 FORMAT(1H0,30HJ          BAFFLE SPACE NUMBER)                     RITE 130
1003 FORMAT(1H0,86H1ST-I      INCREMENT NUMBER OF FIRST INCREMENT WHICHRITE 140
     1 LIES COMPLETELY IN BAFFLE SPACE J)                              RITE 141
1004 FORMAT(1H0,59HDELT-W     CALCULATED TEMPERATURE DROP ACROSS TUBE WRITE 150
     1ALL (F))                                                         RITE 151
1005 FORMAT(1H0,84HDELT-W-A   ALLOWABLE TEMPERATURE DROP ACROSS TUBE WARITE 160
     1LL BASED ON ALLOWABLE STRESS (F))                                RITE 161
1006 FORMAT(1H0,40HT-WALL     WALL MATERIAL TEMPERATURE (F))           RITE 170
1007 FORMAT(1H0,68HDELP-S     CALCULATED SHELL PRESSURE DROP FOR THE BARITE 180
     1FFLE SPACE (PSI))                                                RITE 181
1008 FORMAT(1H0,70HDENS-H     MEAN DENSITY OF THE HOT FLUID FOR THE BAFRITE 190
     1FLE SPACE (LB/FT3))                                              RITE 191
1009 FORMAT(1H0,74HVISC-H     MEAN VISCOSITY OF THE HOT FLUID FOR THE BRITE 200
     1AFFLE SPACE (LB/FT-HR))                                          RITE 201
      END                                                              RITE 210
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      SUBROUTINE RITE3                                                  RITE3 10
      WRITEOUTPUTTAPE51,1001                                            RITE3 20
      WRITEOUTPUTTAPE51,1002                                            RITE3 30
      WRITEOUTPUTTAPE51,1003                                            RITE3 40
      WRITEOUTPUTTAPE51,1004                                            RITE3 50
      WRITEOUTPUTTAPE51,1005                                            RITE3 60
      WRITEOUTPUTTAPE51,1006                                            RITE3 70
      WRITEOUTPUTTAPE51,1007                                            RITE3 80
      WRITEOUTPUTTAPE51,1008                                            RITE3 90
      WRITEOUTPUTTAPE51,1009                                            RITE 100
      WRITEOUTPUTTAPE51,1010                                            RITE 110
      WRITEOUTPUTTAPE51,1011                                            RITE 120
      RETURN                                                            RITE 130
 1001 FORMAT(1H1,//,14X,91H* * *  THE FOLLOWING TABLE GIVES INFORMATION RITE 140
     1AT EACH INCREMENT THROUGH THE EXCHANGER  * * *,//,35X,50HTHE COLUMRITE 141
     2N LABELS FOR THIS TABLE ARE DEFINED BELCW,////)                   RITE 142
 1002 FORMAT(1H0,27HI          INCREMENT NUMBER)                        RITE 150
 1003 FORMAT(1H0,47HLENGTH     TUBE LENGTH FOR THE INCREMENT (FEET))    RITE 160
 1004 FORMAT(1H0,43HT-HOT      TEMPERATURE OF THE HOT FLUID (F))        RITE 170
 1005 FORMAT(1H0,44HT-COLD     TEMPERATURE OF THE CCLD FLUID (F))       RITE 180
 1006 FORMAT(1H0,43HP-COLD     PRESSURE OF THE CCLD FLUID (PSI))        RITE 190
 1007 FORMAT(1H0,53HDELP-C     TUBE PRESSURE DROP FOR THE INCREMENT (PSIRITE 200
     1))                                                                RITE 201
 1008 FORMAT(1H0,77HRES-IN     THERMAL RESISTANCE OF THE INSIDE FILM FORRITE 210
     1 THE INCREMENT (HR-F/BTU))                                        RITE 211
 1009 FORMAT(1H0,79HRES-WALL   THERMAL RESISTANCE OF THE WALL MATERIAL FRITE 220
     1OR THE INCREMENT (HR-F/BTU))                                      RITE 221
 1010 FORMAT(1H0,109HRES-OUT    THERMAL RESISTANCE OF THE OUTSIDE FILM FRITE 230
     1OR THE BAFFLE SPACE IN WHICH THE INCREMENT LIES (HR-F/BTU))       RITE 231
 1011 FORMAT(1H0,90HRES-TOT    TOTAL THERMAL RESISTANCE BETWEEN HOT & CORITE 240
     1LD FLUIDS FOR THE INCREMENT (HR-F/BTU))                           RITE 241
      END                                                               RITE 250
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```
      SUBROUTINE RITE4(NUMT,DS,SDPT,SDPS,DTLME,SX,AREAX,UEQX,SBS,       RITE4  10
     1   AREAB,UEQB,NBS,BSL)                                            RITE4  11
      WRITEOUTPUTTAPE51,1001                                            RITE4  20
      WRITEOUTPUTTAPE51,1002,NUMT                                       RITE4  30
      WRITEOUTPUTTAPE51,1003,NBS                                        RITE4  40
      WRITEOUTPUTTAPE51,1004,BSL                                        RITE4  50
      WRITEOUTPUTTAPE51,1005,DS                                         RITE4  60
      WRITEOUTPUTTAPE51,1006,SDPT                                       RITE4  70
      WRITEOUTPUTTAPE51,1007,SDPS                                       RITE4  80
      WRITEOUTPUTTAPE51,1008,DTLME                                      RITE4  90
      WRITEOUTPUTTAPE51,1009,SX                                         RITE  100
      WRITEOUTPUTTAPE51,1010,AREAX                                      RITE  110
      WRITEOUTPUTTAPE51,1011,UEQX                                       RITE  120
      WRITEOUTPUTTAPE51,1012,SBS                                        RITE  130
      WRITEOUTPUTTAPE51,1013,AREAB                                      RITE  140
      WRITEOUTPUTTAPE51,1014,UEQB                                       RITE  150
      RETURN                                                            RITE  160
 1001 FORMAT(1H1,//,18X,84H* * *  THE FOLLOWING ARE AVERAGE OR TOTAL PRORITE  170
     1PERTIES FOR THE ENTIRE EXCHANGER  * * *,//)                       RITE  171
 1002 FORMAT(1H0,23HTOTAL NUMBER OF TUBES= ,I5)                         RITE  180
 1003 FORMAT(1H0,31HTOTAL NUMBER OF BAFFLE SPACES= ,I4)                 RITE  190
 1004 FORMAT(1H0,32HLENGTH OF A BAFFLE SPACING(FT)= ,F6.3)              RITE  200
 1005 FORMAT(1H0,45HINSIDE DIAMETER OF EXCHANGER SHELL (INCHES)= ,F7.2) RITE  210
 1006 FORMAT(1H0,36HTOTAL PRESSURE DROP IN TUBES (PSI)= ,F8.2)          RITE  220
 1007 FORMAT(1H0,36HTOTAL PRESSURE DROP IN SHELL (PSI)= ,F8.2)          RITE  230
 1008 FORMAT(1H0,23HLOG-MEAN  DELTA-T (F)= ,F7.2,//)                    RITE  240
 1009 FORMAT(1H0,26HTOTAL TUBE LENGTH (FEET)= ,F7.2)                    RITE  250
 1010 FORMAT(1H0,59HTOTAL HEAT TRANSFER AREA BASED ON TOTAL TUBE LENGTH RITE  260
     1(FT2)= ,F8.1)                                                     RITE  261
 1011 FORMAT(1H0,77HOVERALL HEAT TRANSFER COEFFICIENT BASED ON TOTAL TUBRITE  270
     1E LENGTH (BTU/HR-FT2-F)= ,F7.2,//)                                RITE  271
 1012 FORMAT(1H0,34HTOTAL BAFFLE SPACE LENGTH (FEET)= , F7.2)           RITE  280
 1013 FORMAT(1H0,67HTOTAL HEAT TRANSFER AREA BASED ON TOTAL BAFFLE SPACERITE  290
     1 LENGTH (FT2)= ,F8.1)                                             RITE  291
 1014 FORMAT(1H0,85HOVERALL HEAT TRANSFER COEFFICIENT BASED ON TOTAL BAFRITE  300
     1FLE SPACE LENGTH (BTU/HR-FT2-F)= ,F7.2)                           RITE  301
      END                                                               RITE  310
```

```
      SUBROUTINE VISCOS(T,P,ETAP)                                       VISCO 10
      TR = T+460.                                                       VISCO 20
      ETAT = .189E-06*(TR/492.)**.5*(1.+986./492.)/(1.+986./TR)         VISCO 30
      CALL SVH(2,P,T,V,HPT)                                             VISCO 40
      ETAP = 115920.*ETAT*(V/(V-.012))**2                               VISCO 50
      RETURN                                                            VISCO 60
      END                                                               VISCO 70
```

```
      SUBROUTINE CONDT(T,P,COND)                                        CONDT 10
      TR = T+460.                                                       CONDT 20
      CALL SVH(2,P,T,V,HPT)                                             CONDT 30
      COND = 1.093E-06*TR**1.45+28.5375E-04/V**1.25                     CONDT 40
      RETURN                                                            CONDT 50
      END                                                               CONDT 60
```

```
      SUBROUTINE SVH(N,P,T,SVOL,HPT)                                    SVH   10
      COMMON/TP/PRES,TEMP,M1,M2,NC1,NC2,XT,YT                           SVH   20
      GOTO(1,2),N                                                       SVH   30
    1 CALL TIPUT                                                        SVH   40
      RETURN                                                            SVH   50
    2 PRES=P                                                            SVH   60
      TEMP=T                                                            SVH   70
      CALL SPECV(SVOL)                                                  SVH   80
      CALL H(HPT)                                                       SVH   90
      END                                                               SVH  100
```

```
      SUBROUTINE SPECV(ANS)
      COMMON/VOL/C(5,60)
      COMMON/TP/PRES,TEMP,M1,M2,NC1,NC2,XT,YT
      T=(TEMP-550.-1.0E-5)/10.+1.
      NC1=T
      XT=T-NC1
      NC2=NC1+1
      P=(PRES-3500.-1.0E-5)/100.+1.
      M1=P
      YT=P-M1
      M2=M1+1
      IF(M1.LT.1.OR.M1.GT.4)1,2
1     CALL ERROR
2     IF(NC1.LT.1.OR.NC1.GT.55)1,3
3     CONTINUE
      Z11=C(M1,NC1)
      Z12=C(M1,NC2)
      Z21=C(M2,NC1)
      Z22=C(M2,NC2)
      XA=Z11+(Z12-Z11)*XT
      XB=Z21+(Z22-Z21)*XT
      YSET=XA+(XB-XA)*YT
      YA=Z11+(Z21-Z11)*YT
      YB=Z12+(Z22-Z12)*YT
      XSET=YA+(YB-YA)*XT
      ANS=0.5*(YSET+XSET)
      RETURN
      END
```

```
      SUBROUTINE H(ANS)
      COMMON/H/C(5,60)
      COMMON/TP/PRES,TEMP,M1,M2,NC1,NC2,XT,YT
      Z11=C(M1,NC1)
      Z12=C(M1,NC2)
      Z21=C(M2,NC1)
      Z22=C(M2,NC2)
      XA=Z11+(Z12-Z11)*XT
      XB=Z21+(Z22-Z21)*XT
      YSET=XA+(XB-XA)*YT
      YA=Z11+(Z21-Z11)*YT
      YB=Z12+(Z22-Z12)*YT
      XSET=YA+(YB-YA)*XT
      ANS=0.5*(YSET+XSET)
      RETURN
      END
```

```
      SUBROUTINE TIPUT
      COMMON/VOL/V(5,60)
      COMMON/H/H(5,60)
      DO 1 J=1,56
1     READ(50,1001)(V(I,J),I=1,5)
1001  FORMAT(5E10.0)
      DO 2 J=1,56
2     READ(50,1002)(H(I,J),I=1,5)
1002  FORMAT(5E10.0)
      RETURN
      END
```

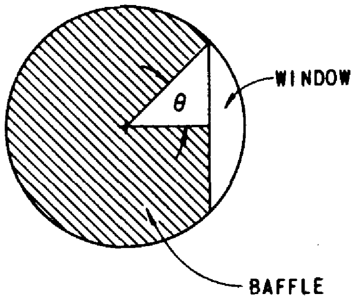
Intermediate Variables

The intermediate variables used in the SUPEX computer program are listed below in the order in which the terms appear in the program. The units in which the variables are expressed in the program are as follows.

Temperature,	°F
Mass,	lb_m
Length,	ft
Pressure,	$lb_f/in.^2$
Density,	lb_m/ft^3
Viscosity,	$lb_f/ft \cdot hr$

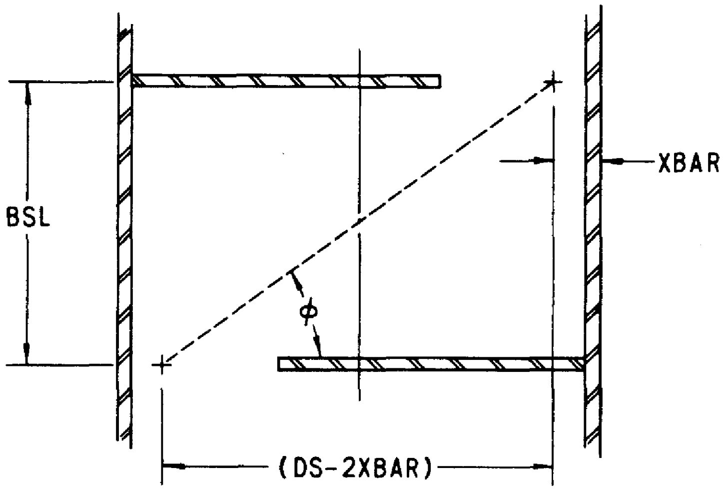
DELPTA	Total allowable pressure drop in the cold fluid (steam).
LOP1, LOP2, ... LOP11	Counters used in the various iteration loops to determine whether the loop has converged within a certain preset number of iterations.
DELTH	Total temperature drop in the hot fluid (salt).
DTPB	Temperature drop in the hot fluid (salt) per baffle space based on the estimated number of baffle spaces (GNB).
BSL	Baffle spacing length.
DTI	Inside diameter of tubes.
TCAV	Average temperature of the cold fluid (steam).
PCAV	Average pressure of the cold fluid (steam).
SPV1	Inlet specific volume of the cold fluid (steam).
DUM	A dummy variable.
SPV2	Outlet specific volume of the cold fluid (steam).
SPVAV	Average specific volume of the cold fluid (steam).
SPVG	A guess at the mean value of the specific volume of the cold fluid (steam) used in making an initial estimate of the mass flow rate of the cold fluid.
VIS1	Inlet viscosity of the cold fluid (steam).
VIS2	Outlet viscosity of the cold fluid (steam).
VISAV	Average viscosity of the cold fluid (steam).
VISG	A guess at the mean value of the viscosity of the cold fluid (steam) used in making an initial estimate of the Reynolds number for the cold fluid.

CFG	A guess at the value of the friction factor for the cold fluid (steam).
THETAL	The minimum value of the angle THETA (radians), where THETA is half of the angle subtended by the chord that is formed by the window region of the baffle. The value 0.8 corresponds to θ = 45°; this value is just a guess used to start the iteration process.

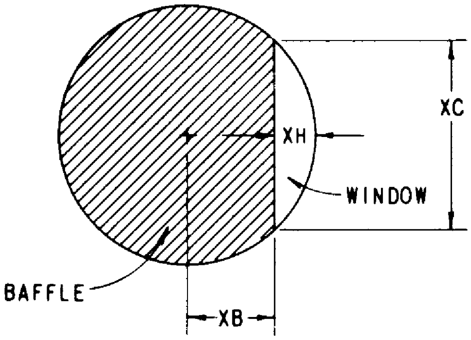


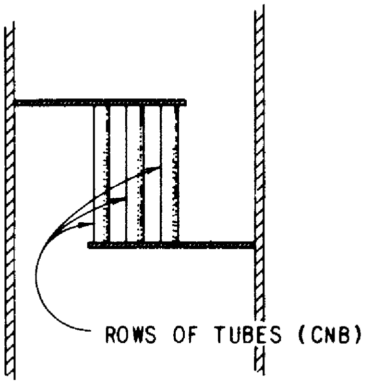
PERCL	The ratio of the window area to the total cross-sectional area at the baffle, based on THETAL.
THETAU	The maximum value of the angle THETA. The value of 1.5707 corresponds to θ = 90°.
PERCU	The ratio of the window area to the total cross-sectional area at the baffle, based on THETAU.
NEW	The value of THETA based on the iteration scheme.
PNEW	The ratio of the window area to the total cross-sectional area at the baffle, based on NEW.
EPNEW	The absolute difference between the desired fractional window cut (PW) and the calculated fractional window cut (PNEW).
THETAC	The calculated value of THETA that gives the desired value of the fractional window cut.
G	Mass velocity (density times flow speed) for the cold fluid (steam).
REG	Reynolds number for the cold fluid (steam) based on an estimate of the viscosity of the cold fluid.
CFC	Calculated friction factor for the cold fluid (steam).
DIFA	Absolute difference between the calculated and guessed values of the friction factor for the cold fluid (steam).
NUMT	Number of tubes required.
BNUMT	Floating point conversion value of the integer NUMT.
DS	Inside diameter of the shell of the heat exchanger.

XBAR	Distance from the inside surface of the shell to the centroid of the window area at a baffle.



BRL1	Tangent of the angle ϕ, as illustrated in sketch above.
GBRL	$(0.77/\mathrm{BRL1}^{0.138})$ This factor is a multiplicative correction factor developed to modify Bergelin's correlation in cases where the baffle spacing becomes large relative to the diameter of the shell. In such cases, the flow in the middle of the baffle region is essentially parallel.
AW	Window area at a baffle.
AX	Baffle area (total cross-sectional area minus window area).
AXC	A value of AX calculated from a value of THETA.
DIFB	Absolute difference between AXC and AX.
THETA2	A value of the angle THETA based on the value of AXC.
AXC2	A value of AXC based on the value of THETA2.
GC	Mass velocity (density times flow speed) for the cold fluid (steam) based on the current number of tubes in the exchanger (NUMT).
XB	Distance from the axial center line to the window edge of the baffle.
CNB	Number of rows of tubes from the window edge of one baffle to the window edge of the following baffle.





XH	Inside radius of the shell minus XB.
CNW	Number of rows of tubes in one window.
XC	Chord length of the window edge of the baffle.
PCFB	Fraction of the distance between tube centers that is free for cross flow.
SBK	Average free area in cross flow per unit baffle spacing.
SW	Free hot-fluid (salt) area in the window region.
SDPT	Summed pressure drop on the tube side.
SDPS	Summed pressure drop on the shell side.
MS	A counter which has a value of 1 for the first calculation in each baffle space and a value of zero for the rest of the incremental calculations in the baffle space.
SX	Summed tube length.
SBS	Summed baffle space length.
TC(I)	Temperature of the cold fluid (steam) at the beginning of the I-th increment.
TH(I)	Temperature of the hot fluid (salt) at the beginning of the I-th increment.
RWK	A factor used to calculate the heat transfer resistance of the tube wall material. It can be thought of as an effective thickness of the tube wall. If

$$R_W = \frac{d_o}{2k}\left(\ln \frac{d_o}{d_i}\right),$$

where

R_W = thermal resistance of tube wall material,
d_o = outside diameter of tube,
k = thermal conductivity of wall material, and
d_i = inside diameter of tube; then

$$RWK = R_W k .$$

PC(I)	Pressure of the cold fluid (steam) at the beginning of the I-th increment.
HC(I)	Enthalpy of the cold fluid (steam) at the beginning of the I-th increment.
BN	Floating point conversion of the integer N (c.f. input variables).
QX	The amount of heat to be transferred in each increment.
DECT	The change in temperature per increment of the hot fluid (salt).
DECH	The change in enthalpy per increment of the cold fluid (steam).
I	Subscript index which refers to the increments.
K	Subscript index which refers to the baffle spaces.
SB	Total cross-flow area for the hot fluid (salt) in a given baffle space.
TCON	An estimate of the bulk temperature of the hot fluid (salt) in a baffle space.
DENH	Density of the hot fluid (salt) based on the temperature (TCON).
VISH	Viscosity of the hot fluid (salt) based on the temperature (TCON).
DHOT(K)	Density of the hot fluid (salt) for the K-th baffle space.
VHOT(K)	Viscosity of the hot fluid (salt) for the K-th baffle space.
CON1	The Prandtl number for the hot fluid (salt) raised to the 2/3 power.
GM	Mass velocity (density times flow speed) of the hot fluid (salt) in cross flow.
RECB	The cross-flow Reynolds number for the hot fluid (salt).
HJB	The effect of the cross-flow Reynolds number on the shell-side convective heat transfer coefficient.
HB	The shell-side convective heat transfer coefficient for cross flow.
GW	Mass velocity (density times flow speed) of the hot fluid (salt) in parallel flow.
GS	A kind of root-mean-square mass velocity for the hot fluid (salt). It is used in the Bergelin correlations.
RECW	The parallel-flow Reynolds number for the hot fluid (salt).
HJW	The effect of the parallel-flow Reynolds number on the shell-side convective heat transfer coefficient.

HW	The shell-side convective heat transfer coefficient for parallel flow.
HO	The total shell-side convective heat transfer coefficient.
RO(K)	The film resistance to heat transfer on the outside of the tubes for the K-th baffle space.
TH(I+1)	Temperature of the hot fluid (salt) at the end of the I-th increment (i.e. the beginning of the I+1-th increment).
DELPP	Tube-side change in pressure for a given increment.
HCG	An estimate of the enthalpy of the cold fluid (steam) at the end of the I-th increment based on the estimated pressure and temperature at the end of the I-th increment.
EH	The absolute difference between HCG and the HC(I+1) which has been calculated based on the heat transferred per increment (QX/WC).
TRIAL	A trial value of TC(I+1) to be used for iteration.
HRIAL	A trial value of HC(I+1) to be used for iteration.
TNEXT	A value of TC(I+1) which is determined by the iteration scheme (i.e. a new estimate of TC(I+1) to start the next iteration).
DENOM	The antilog of the denominator of the defining equation for a logarithmic mean temperature difference.
TDEN	The absolute difference between DENOM and unity.
DELTLM	Logarithmic mean temperature difference.
TM	Average temperature of the cold fluid (steam) in the I-th increment.
PM	Average pressure of the cold fluid (steam) in the I-th increment.
SPVB	Specific volume of the cold fluid based on the average temperature and pressure, TM and PM, in the increment.
HFB	Enthalpy of the cold fluid (steam) based on the average temperature and pressure, TM and PM, in the increment.
VISB	Viscosity of the cold fluid (steam) based on the average temperature and pressure, TM and PM, in the increment.
TW	Temperature of the wall material in the increment.
TCW	Thermal conductivity of the wall material in the increment.
RW(I)	Thermal resistance of the wall material in the I-th increment.
DTFM	Difference between temperature of inside wall and temperature of bulk cold fluid (steam) for the increment.
TMS	Mean temperature of the tube wall surface in the increment.

SPVI	Specific volume of the cold fluid (steam) based on the average pressure and mean tube-wall surface temperature, PM and TMS, in the increment.
HFI	Enthalpy of the cold fluid (steam) based on the average pressure and mean tube-wall surface temperature, PM and TMS, in the increment.
TCFI	Thermal conductivity of the cold fluid (steam) based on the average pressure and mean tube-wall surface temperature, PM and TMS, in the increment.
VISFI	Viscosity of the cold fluid (steam) based on the average pressure and mean tube-wall surface temperature, PM and TMS, in the increment.
CRE	Reynolds number of the cold fluid (steam), based on the inside tube wall conditions, raised to the 0.923 power.
CPR	Prandtl number of the cold fluid, based on inside tube wall conditions and a fictitious specific heat, raised to the 0.613 power. The fictitious specific heat is defined as $$\frac{H_i - H_b}{T_i - T_b}$$ where H is enthalpy, T is temperature and the subscripts "i" and "b" refer to inside tube surface and bulk cold fluid (steam), respectively. This definition of specific heat is necessary since specific heat as normally defined is indeterminant at the critical point, while enthalpy, although discontinuous at the critical point, is not indeterminant.
CSV	The ratio of the bulk specific heat of the cold fluid (steam) to the specific heat of the cold fluid evaluated at inside tube-wall conditions raised to the 0.231 power.
HI	Convective heat transfer coefficient over the increment for the inside surface of the tube wall.
RI(I)	The thermal resistance of the convective film on the inside surface of the tubes, for the I-th increment, adjusted to the outside diameter of the tube.
RT(I)	The total thermal resistance between the hot (salt) and cold (steam) fluids for the I-th increment.
DTFMC	The temperature drop across the inside tube wall convective film for the increment.
DTFM2	Arithmetic average of DTFM and DTFMC.
TMS2	New estimate of the mean tube-wall surface temperature based on DTFM2.

SPVI2	New estimate of the specific volume of the cold fluid (steam) based on average pressure (PM) and the new estimate of the mean tube-wall surface temperature (TMS2) for the increment.
HFI2	New estimate of the enthalpy of the cold fluid (steam) based on the average pressure (PM) and the new estimate of the mean tube-wall surface temperature (TMS2) for the increment.
TCFI2	New estimate of the thermal conductivity of the cold fluid (steam) based on the average pressure (PM) and the new estimate of the mean tube-wall surface temperature (TMS2) for the increment.
VISFI2	New estimate of the viscosity of the cold fluid (steam) based on the average pressure (PM) and the new estimate of the mean tube-wall surface temperature (TMS2) for the increment.
CRE2	New estimate of CRE based on VISFI2.
CPR2	New estimate of CPR based on HFI2, TMS2, VISFI2, and TCFI2.
CSV2	New estimate of CSV based on SPVI2.
H2I	New estimate of HI based on TCFI2, CRE2, CPR2, and CSV2.
R2I	New estimate of RI(I) based on H2I.
R2T	New estimate of RT(I) based on R2I.
DTFMC2	New estimate of DTFMC based on R2I and R2T.
SLOPE	A ratio of two differences between various estimates of the temperature drop across the inside tube wall convective film for the increment. This is used to make a new estimate of DTFM in order to continue the iteration process.
U(I)	Overall heat transfer coefficient for the I-th increment based on the outside diameter of the tube.
X(I)	Tube length in the I-th increment.
RE	Reynolds number for the cold fluid (steam) based on the bulk viscosity (VISB) of the increment.
CFI	Fanning friction factor for the cold fluid (steam) for the increment.
DELP(I)	The pressure drop for the cold fluid (steam) in the I-th increment.
DIFC	The difference between two consecutive values of the pressure drop for the cold fluid in the I-th increment as determined by consecutive passes through the iteration loop.
IBK(K)	The value of the index I at the beginning of the first increment that is totally contained within the K-th baffle space.

ALPHA	Coefficient of thermal expansion for the tube wall material (x 10^6).
ETW	Modulus of elasticity for the tube wall material (x 10^{-6}).
CON2, CON3	Factors in the expression which calculate the stress components in the tube wall.
B, SL	Constants in the expression given in Section III of the ASME Boiler and Pressure Vessel Code for calculating the allowable thermal stress components.
CON4	Term for the allowable thermal stress components given in Section III of the ASME Boiler and Pressure Vessel Code.
TWALL(K)	Temperature of tube wall material for the K-th baffle space.
DELTWA(K)	Allowable temperature difference across the tube wall for the K-th baffle space based on allowable thermal stresses.
DELTW(K)	Temperature difference across the tube wall for the K-th baffle space.
BWN	Factor used in shell-side pressure drop calculations. The factor takes the value 0.5 if the increment is at either end of the exchanger, and it takes the value of unity for all other increment positions.
DELPSB	Shell-side pressure drop in the baffle space area.
DELPSW	Shell-side pressure drop in the window area.
DELPS(K)	Total shell-side pressure drop for the K-th baffle space.
EDPT	Absolute difference between the total calculated tube-side pressure drop and the allowable total tube-side pressure drop.
EDPS	Absolute difference between the total calculated shell-side pressure drop and the allowable total shell-side pressure drop.
J, JN, JNC	Counters to put the baffle space information out in groups of 50 per page.
NBS	Total number of baffle spaces.
IN, INC	Counters to put the increment information out in groups of 50 per page.
RO(I)	The film resistance to heat transfer on the outside of the tubes for the I-th increment.
AREAX	Total heat transfer area based on total tube length.
UEQX	Overall heat transfer coefficient based on total tube length.
AREAB	Total heat transfer area based on total baffle space length.
UEQB	Overall heat transfer coefficient based on total baffle space length.

Subroutines

There are ten subroutines in the SUPEX computer program. The terms used for each of these subroutines are listed below with a brief description of the purpose of each subroutine.

RITE1	Writes out the input information.
RITE2	Writes out definitions of the various columns in the table of output for each baffle space.
RITE3	Writes out definitions of the various columns in the table of output for each increment.
RITE4	Writes out information concerning the average or total properties for the entire exchanger.
VISCOS(T, P, ETAP)	Calculates the viscosity of the cold fluid (steam) for a given temperature and pressure.
CONDT(T, P, COND)	Calculates the thermal conductivity of the cold fluid (steam) for a given temperature and pressure.
SVH(N,P,T, SVOL, HPT)	Calls the subroutine TIPUT when N = 1 or calls subroutines SPECV and H when N = 2.
SPECV(ANS)	Calculates, using an interpolation of input data, the specific volume of the cold fluid (steam).
H(ANS)	Calculates, using an interpolation of input data, the specific enthalpy of the cold fluid (steam).
TIPUT	Reads in an array of values of specific volume and specific enthalpy as functions of temperature and pressure.

Computer Input and Output for Reference MSBR Steam Generator Superheater

```
                    * * *  THE FOLLOWING IS THE INPUT INFORMATION FOR THIS PROBLEM  * * *

OUTSIDE DIAMETER OF TUBES (INCHES)=  0.500

TUBE WALL THICKNESS (INCHES)=  0.0770

TUBE PITCH (INCHES)=  0.8750

NUMBER OF INCREMENTS INTO WHICH THE EXCHANGER IS DIVIDED=  100


INLET TEMPERATURE OF HOT FLUID (F)=  1150.0

OUTLET TEMPERATURE OF HOT FLUID (F)=   850.0

INLET TEMPERATURE OF COLD FLUID (F)=   700.0

OUTLET TEMPERATURE OF COLD FLUID (F)=  1000.0


OUTLET PRESSURE OF COLD FLUID (PSI)=  3600.0

ALLOWABLE TOTAL PRESSURE DROP ON TUBE SIDE (PSI)=   150.0

ALLOWABLE TOTAL PRESSURE DROP ON SHELL SIDE (PSI)=    60.0


MASS FLOW RATE OF COLD FLUID (LB/HR)=  6.330E 05

MASS FLOW RATE OF HOT FLUID (LB/HR)=  3.820E 06

TOTAL HEAT TRANSFER RATE (BTU/HR)=  4.120E 08

SPECIFIC HEAT OF HOT FLUID (BTU/LB-F)=  0.360

THERMAL CONDUCTIVITY OF HOT FLUID (BTU/HR-FT-F)=  0.240

FRACTIONAL WINDOW CUT=  0.40
```

Computer Input Data for Reference MSBR Steam Generator Superheater (continued)

```
BY-PASS LEAKAGE FACTOR FOR PRESSURE=  0.520

BY-PASS LEAKAGE FACTOR FOR HEAT TRANSFER=  0.800


ESTIMATE OF THE NUMBER OF BAFFLE SPACES REQUIRED=  18

ESTIMATE OF THE LENGTH OF A BAFFLE SPACE(FT)=  3.00

ESTIMATE OF THE TOTAL TUBE LENGTH(FT)=  65.00
```

```
       * * *  THE FOLLOWING TABLE GIVES INFORMATION FOR EACH BAFFLE SPACE THROUGH THE EXCHANGER  * * *
                                THE COLUMN LABELS FOR THIS TABLE ARE DEFINED BELOW


J             BAFFLE SPACE NUMBER

1ST-I         INCREMENT NUMBER OF FIRST INCREMENT WHICH LIES COMPLETELY IN BAFFLE SPACE J

DELT-W        CALCULATED TEMPERATURE DROP ACROSS TUBE WALL (F)

DELT-W-A      ALLOWABLE TEMPERATURE DROP ACROSS TUBE WALL BASED ON ALLOWABLE STRESS (F)

T-WALL        WALL MATERIAL TEMPERATURE (F)

DELP-S        CALCULATED SHELL PRESSURE DROP FOR THE BAFFLE SPACE (PSI)

DENS-H        MEAN DENSITY OF THE HOT FLUID FOR THE BAFFLE SPACE (LB/FT3)

VISC-H        MEAN VISCOSITY OF THE HOT FLUID FOR THE BAFFLE SPACE (LB/FT-HR)

                  J     1ST-I    DELT-W    DELT-W-A   T-WALL    DELP-S    DENS-H    VISC-H
                 ----   ------   -------   --------   ------    ------    ------    ------

                  1        1      53.05      90.73    1061.5     1.785    113.2     2.630
                  2        5      61.14     106.37    1036.8     3.391    113.5     2.681
                  3       10      70.73     121.20    1007.0     3.380    113.9     2.746
                  4       15      78.72     124.90     979.9     3.369    114.3     2.815
                  5       20      86.70     128.62     953.0     3.358    114.6     2.886
                  6       26      94.22     132.70     923.9     3.345    115.1     2.976
                  7       32     100.01     136.45     897.4     3.332    115.5     3.071
                  8       38     104.06     139.87     873.5     3.320    116.0     3.172
                  9       44     106.05     142.89     852.6     3.307    116.4     3.278
                 10       51     105.97     145.94     831.8     3.292    116.9     3.411
                 11       57     103.91     148.16     816.8     3.280    117.4     3.531
                 12       63     100.40     150.07     803.9     3.268    117.8     3.660
                 13       69      95.38     151.64     793.4     3.255    118.3     3.796
                 14       74      90.69     152.83     785.5     3.245    118.6     3.917
                 15       79      85.40     153.88     778.5     3.235    119.0     4.044
                 16       84      80.07     154.92     771.7     3.225    119.4     4.178
                 17       89      74.71     155.94     765.0     3.215    119.7     4.320
                 18       93      70.78     156.83     759.1     3.207    120.0     4.439
                 19       97      67.27     157.81     752.7     3.199    120.3     4.564
```

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            * * *  THE FOLLOWING TABLE GIVES INFORMATION AT EACH INCREMENT THROUGH THE EXCHANGER  * * *
                              THE COLUMN LABELS FOR THIS TABLE ARE DEFINED BELOW



I           INCREMENT NUMBER

LENGTH      TUBE LENGTH FOR THE INCREMENT (FEET)

T-HOT       TEMPERATURE OF THE HOT FLUID (F)

T-COLD      TEMPERATURE OF THE COLD FLUID (F)

P-COLD      PRESSURE OF THE COLD FLUID (PSI)

DELP-C      TUBE PRESSURE DROP FOR THE INCREMENT (PSI)

RES-IN      THERMAL RESISTANCE OF THE INSIDE FILM FOR THE INCREMENT (HR-F/BTU)

RES-WALL    THERMAL RESISTANCE OF THE WALL MATERIAL FOR THE INCREMENT (HR-F/BTU)

RES-OUT     THERMAL RESISTANCE OF THE OUTSIDE FILM FOR THE BAFFLE SPACE IN WHICH THE INCREMENT LIES (HR-F/BTU)

RES-TOT     TOTAL THERMAL RESISTANCE BETWEEN HOT & COLD FLUIDS FOR THE INCREMENT (HR-F/BTU)


       I     LENGTH    T-HOT     T-COLD     P-COLD    DELP-C     RES-IN    RES-WALL     RES-OUT     RES-TOT
     -----   ------   -------   -------   --------   ------   --------   --------    --------    --------

       1      1.076    1150.0    1000.0     3600.0    4.390   0.000476   0.000721    0.000842    0.002039
       2      1.038    1147.0     993.5     3604.4    4.173   0.000473   0.000724    0.000842    0.002039
       3      1.002    1144.0     982.9     3608.5    3.979   0.000469   0.000727    0.000842    0.002039
       4      0.975    1141.0     976.4     3612.5    3.821   0.000464   0.000730    0.000842    0.002037
       5      0.951    1138.0     967.9     3616.3    3.679   0.000460   0.000733    0.000847    0.002039
       6      0.924    1135.0     961.4     3620.0    3.528   0.000455   0.000736    0.000847    0.002038
       7      0.899    1132.0     952.4     3623.5    3.385   0.000451   0.000739    0.000847    0.002036
       8      0.882    1129.0     945.9     3626.9    3.279   0.000447   0.000742    0.000847    0.002036
       9      0.859    1126.0     939.4     3630.2    3.147   0.000442   0.000745    0.000847    0.002034
      10      0.839    1123.0     930.3     3633.3    3.030   0.000438   0.000748    0.000853    0.002038
      11      0.824    1120.0     923.8     3636.4    2.937   0.000434   0.000751    0.000853    0.002037
      12      0.809    1117.0     917.3     3639.3    2.845   0.000429   0.000753    0.000853    0.002035
      13      0.794    1114.0     910.8     3642.1    2.756   0.000424   0.000756    0.000853    0.002033
      14      0.780    1111.1     904.3     3644.9    2.670   0.000420   0.000759    0.000853    0.002031
```

15	0.768	1108.1	897.8	3647.6	2.592	0.000414	0.000761	0.000859	0.002034
16	0.755	1105.1	891.3	3650.2	2.510	0.000409	0.000764	0.000859	0.002032
17	0.742	1102.1	884.7	3652.7	2.430	0.000404	0.000767	0.000859	0.002030
18	0.729	1099.1	878.2	3655.1	2.350	0.000398	0.000770	0.000859	0.002026
19	0.718	1096.1	871.7	3657.5	2.282	0.000392	0.000772	0.000859	0.002023
20	0.710	1093.1	866.3	3659.7	2.223	0.000387	0.000775	0.000865	0.002027
21	0.701	1090.1	859.8	3662.0	2.161	0.000381	0.000778	0.000865	0.002024
22	0.694	1087.1	855.0	3664.1	2.109	0.000376	0.000780	0.000865	0.002021
23	0.686	1084.1	849.8	3666.2	2.054	0.000371	0.000782	0.000865	0.002018
24	0.679	1081.1	844.5	3668.3	2.002	0.000366	0.000785	0.000865	0.002015
25	0.672	1078.1	839.3	3670.3	1.950	0.000360	0.000787	0.000865	0.002011
26	0.668	1075.1	834.5	3672.2	1.909	0.000354	0.000789	0.000872	0.002016
27	0.662	1072.1	829.7	3674.1	1.862	0.000349	0.000792	0.000872	0.002012
28	0.657	1069.1	824.9	3676.0	1.818	0.000344	0.000794	0.000872	0.002010
29	0.652	1066.1	820.2	3677.8	1.775	0.000338	0.000796	0.000872	0.002006
30	0.647	1063.1	815.9	3679.6	1.734	0.000332	0.000798	0.000872	0.002002
31	0.643	1060.1	811.7	3681.3	1.694	0.000325	0.000800	0.000872	0.001998
32	0.641	1057.1	807.6	3683.0	1.662	0.000319	0.000802	0.000880	0.002002
33	0.637	1054.1	803.4	3684.7	1.626	0.000314	0.000804	0.000880	0.001998
34	0.634	1051.1	799.5	3686.3	1.590	0.000309	0.000806	0.000880	0.001995
35	0.631	1048.1	795.7	3687.9	1.556	0.000303	0.000808	0.000880	0.001991
36	0.628	1045.1	792.1	3689.5	1.523	0.000297	0.000810	0.000880	0.001987
37	0.626	1042.1	788.6	3691.0	1.490	0.000290	0.000812	0.000880	0.001982
38	0.626	1039.1	785.2	3692.5	1.464	0.000284	0.000814	0.000888	0.001986
39	0.625	1036.1	781.9	3693.9	1.436	0.000280	0.000815	0.000888	0.001983
40	0.623	1033.2	778.9	3695.4	1.407	0.000273	0.000817	0.000888	0.001979
41	0.622	1030.2	775.9	3696.8	1.379	0.000267	0.000819	0.000888	0.001974
42	0.621	1027.2	773.0	3698.2	1.353	0.000261	0.000820	0.000888	0.001969
43	0.620	1024.2	770.3	3699.5	1.328	0.000254	0.000822	0.000888	0.001964
44	0.622	1021.2	767.8	3700.9	1.307	0.000247	0.000823	0.000897	0.001967
45	0.622	1018.2	765.2	3702.2	1.282	0.000241	0.000825	0.000897	0.001963
46	0.623	1015.2	762.8	3703.4	1.260	0.000236	0.000826	0.000897	0.001958
47	0.623	1012.2	760.6	3704.7	1.239	0.000230	0.000827	0.000897	0.001954
48	0.624	1009.2	758.5	3705.9	1.215	0.000223	0.000829	0.000897	0.001949
49	0.624	1006.2	756.4	3707.2	1.193	0.000216	0.000830	0.000897	0.001943
50	0.625	1003.2	754.4	3708.3	1.173	0.000210	0.000831	0.000897	0.001938
51	0.630	1000.2	752.7	3709.5	1.159	0.000205	0.000832	0.000907	0.001944
52	0.632	997.2	750.7	3710.7	1.142	0.000199	0.000834	0.000907	0.001940
53	0.635	994.2	749.3	3711.8	1.123	0.000193	0.000835	0.000907	0.001935
54	0.637	991.2	747.9	3712.9	1.104	0.000186	0.000836	0.000907	0.001928
55	0.639	988.2	746.5	3714.0	1.086	0.000179	0.000837	0.000907	0.001923
56	0.642	985.2	745.1	3715.1	1.071	0.000174	0.000838	0.000907	0.001918
57	0.649	982.2	744.0	3716.2	1.061	0.000168	0.000839	0.000916	0.001923
58	0.652	979.2	742.7	3717.3	1.044	0.000163	0.000840	0.000916	0.001918
59	0.655	976.2	741.4	3718.3	1.027	0.000157	0.000841	0.000916	0.001914
60	0.659	973.2	740.0	3719.3	1.010	0.000152	0.000841	0.000916	0.001909
61	0.663	970.2	739.3	3720.3	0.995	0.000145	0.000842	0.000916	0.001903
62	0.668	967.2	738.5	3721.3	0.982	0.000139	0.000843	0.000916	0.001898

```
    I    LENGTH    T-HOT     T-COLD     P-COLD    DELP-C    RES-IN    RES-WALL    RES-OUT    RES-TOT
  -----  ------   -------   -------   --------   ------   --------   --------   --------   --------

    63   0.677     964.2     737.8     3722.3    0.975   0.000134   0.000844   0.000925   0.001903
    64   0.682     961.2     737.2     3723.3    0.963   0.000129   0.000844   0.000925   0.001898
    65   0.687     958.3     736.5     3724.3    0.948   0.000123   0.000845   0.000925   0.001893
    66   0.693     955.3     735.7     3725.2    0.935   0.000119   0.000846   0.000925   0.001890
    67   0.699     952.3     735.0     3726.1    0.922   0.000115   0.000847   0.000925   0.001887
    68   0.706     949.3     734.3     3727.1    0.909   0.000111   0.000847   0.000925   0.001884
    69   0.716     946.3     733.7     3728.0    0.902   0.000107   0.000848   0.000935   0.001890
    70   0.723     943.3     733.0     3728.9    0.889   0.000104   0.000849   0.000935   0.001888
    71   0.730     940.3     732.3     3729.8    0.877   0.000101   0.000849   0.000935   0.001886
    72   0.738     937.3     731.6     3730.6    0.865   0.000099   0.000850   0.000935   0.001884
    73   0.746     934.3     731.0     3731.5    0.853   0.000096   0.000851   0.000935   0.001882
    74   0.756     931.3     730.3     3732.4    0.845   0.000092   0.000852   0.000943   0.001887
    75   0.765     928.3     729.7     3733.2    0.838   0.000091   0.000852   0.000943   0.001887
    76   0.774     925.3     729.0     3734.1    0.831   0.000090   0.000853   0.000943   0.001886
    77   0.784     922.3     728.4     3734.9    0.826   0.000089   0.000854   0.000943   0.001886
    78   0.793     919.3     727.8     3735.7    0.821   0.000088   0.000854   0.000943   0.001885
    79   0.807     916.3     727.2     3736.5    0.818   0.000087   0.000855   0.000952   0.001894
    80   0.817     913.3     726.5     3737.3    0.812   0.000086   0.000856   0.000952   0.001894
    81   0.828     910.3     725.9     3738.2    0.807   0.000085   0.000857   0.000952   0.001893
    82   0.838     907.3     725.3     3739.0    0.802   0.000084   0.000857   0.000952   0.001893
    83   0.849     904.3     724.7     3739.8    0.796   0.000083   0.000858   0.000952   0.001892
    84   0.865     901.3     724.0     3740.6    0.794   0.000082   0.000859   0.000961   0.001901
    85   0.876     898.3     723.4     3741.4    0.787   0.000081   0.000859   0.000961   0.001901
    86   0.888     895.3     722.7     3742.1    0.780   0.000080   0.000860   0.000961   0.001901
    87   0.901     892.3     722.0     3742.9    0.774   0.000080   0.000861   0.000961   0.001902
    88   0.913     889.3     721.4     3743.7    0.768   0.000080   0.000862   0.000961   0.001902
    89   0.931     886.3     720.7     3744.5    0.765   0.000080   0.000862   0.000970   0.001912
    90   0.944     883.3     720.1     3745.2    0.760   0.000082   0.000863   0.000970   0.001915
    91   0.956     880.4     718.6     3746.0    0.758   0.000088   0.000865   0.000970   0.001922
    92   0.968     877.4     717.1     3746.8    0.755   0.000094   0.000866   0.000970   0.001929
    93   0.985     874.4     715.6     3747.5    0.756   0.000100   0.000867   0.000978   0.001945
    94   0.999     871.4     714.0     3748.3    0.755   0.000107   0.000868   0.000978   0.001953
    95   1.014     868.4     712.7     3749.0    0.754   0.000114   0.000869   0.000978   0.001961
    96   1.027     865.4     711.2     3749.8    0.750   0.000122   0.000870   0.000978   0.001970
    97   1.040     862.4     709.3     3750.5    0.750   0.000127   0.000872   0.000985   0.001984
    98   1.049     859.4     706.9     3751.3    0.746   0.000134   0.000873   0.000985   0.001992
    99   1.057     856.4     704.5     3752.0    0.742   0.000141   0.000875   0.000985   0.002001
   100   1.066     853.4     702.0     3752.8    0.739   0.000149   0.000877   0.000985   0.002011
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* * *  THE FOLLOWING ARE AVERAGE OR TOTAL PROPERTIES FOR THE ENTIRE EXCHANGER  * * *

TOTAL NUMBER OF TUBES=   393

TOTAL NUMBER OF BAFFLE SPACES=   19

LENGTH OF A BAFFLE SPACING(FT)=  3.980

INSIDE DIAMETER OF EXCHANGER SHELL (INCHES)=   18.21

TOTAL PRESSURE DROP IN TUBES (PSI)=   153.53

TOTAL PRESSURE DROP IN SHELL (PSI)=    61.01

LOG-MEAN  DELTA-T (F)=  150.00


TOTAL TUBE LENGTH (FEET)=   76.38

TOTAL HEAT TRANSFER AREA BASED ON TOTAL TUBE LENGTH (FT2)=   3929.3

OVERALL HEAT TRANSFER COEFFICIENT BASED ON TOTAL TUBE LENGTH (BTU/HR-FT2-F)=  699.02


TOTAL BAFFLE SPACE LENGTH (FEET)=   75.61

TOTAL HEAT TRANSFER AREA BASED ON TOTAL BAFFLE SPACE LENGTH (FT2)=   3889.9

OVERALL HEAT TRANSFER COEFFICIENT BASED ON TOTAL BAFFLE SPACE LENGTH (BTU/HR-FT2-F)=  706.10
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