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THERMAL ANALYSIS OF NL 10/24 SHIPPING CASK BASKET

INTRODUCTION

An existing shipping cask, the NL 10/24, has been proposed for shipping breeder reactor fuel assemblies. A basket is being designed to hold a number of fuel assemblies in the cavity of the cask. Each breeder fuel assembly consists of 219 fuel pins inside a hexagonal shell. The basket must support the fuel assemblies, provide sufficient neutron absorption to prevent criticality, and provide adequate heat transfer to prevent fuel pin damage. Because the temperature limit for the fuel pins has not yet been determined, the basket designers need predictions of the maximum fuel pin temperature as a function of thermal power per assembly. The proposed design calls for the cask to be filled with argon when it is vertical and helium when it is horizontal. This report describes calculational methods for determining fuel pin temperatures in the NL 10/24 cask and gives results of calculations for both filler gases.

SUMMARY

Equations were derived for the steady state rate of heat transfer by radiation between the solid surfaces and free convection and conduction in the filler gas. A computer program was written to solve the equations and find the maximum fuel pin temperature as a function of thermal power per assembly. It was concluded that the maximum pin temperature for any assembly is strongly dependent on its power output and only weakly dependent on the power output of other assemblies in the array as shown in Figures 8 and 9.

DISCUSSION

Description of Basket and Fuel Assemblies

A cross sectional view of the basket for the NL 10/24 cask is sho gure 1. The outside surface of the cask is a cylinder eighteen feet long. The basket supports a number of fuel assemblies which are bundles of 219 fuel pins housed in a hexagonal casing. Only the central three foot section of the pins is heated by radioactive decay. At the outer surface of the basket, a heat sink is held at constant temperature by an external cooling system. The outside surface of the fuel assembly is stainless steel with an assumed emissivity of 0.25. The basket is constructed from poison plates which are made from boron steel and have an emissivity of 0.80. The basket design includes supports for the fuel assemblies. These supports are not shown in Figure 1, however the design calls for them to be so open that they do not significantly affect heat transfer.

The analysis considered two different orientations of the cask. First, the cask was assumed to be vertical and filled with argon at one atmosphere, as is the case when the cask is being loaded. Second, the cask was assumed to be horizontal and filled with helium at four atmospheres, as is the case when the cask is being transported.

Heat Transfer Analysis: Pins to Hexagonal Shell

A fuel pin releases both heat and gamma radiation. Some of the gamma radiation converts to heat in other fuel pins and the basket structure. The rest penetrates the shielding. For this analysis, the total energy release from the pins was assumed to be heat. This is a conservative assumption that will make the calculated pin temperatures slightly higher than for the actual case.

Another conservative assumption made was that all of the heat is transferred radially from the pins to the hexagonal shell. In reality, some heat would be transferred axially by conduction through the inactive portions of the pins, then by conduction through the filler gas and radiation to the portion of the hexagonal shell in the ends of the cask. This conservatism is small because the effect of the axial heat loss by conduction through the pins on the temperature and radial heat flux in the center of the active portion of the pins would be small. The axial heat transfer by radiation and filler gas convection would be slight because of the close spacing of the pins within the hexagonal shell.

The flow of heat away from the fuel pins was considered to occur in two stages. First, heat is transferred from the fuel pins to the hexagonal shell surrounding them. Second, heat is transferred from the shell to the constant temperature heat sink surrounding the basket.

Morin[1] analyzed heat transfer from the fuel pins to the hexagonal shell. He concluded that free convection was not important. He therefore considered heat transfer by conduction in the filler gas and thermal radiation. Using the Morin analysis, S. D. Harris wrote a computer program to calculate the maximum pin temperature as a function of assembly decay power and the temperature of the hexagonal shell. The thermal conductivity of the filler gas was an input parameter.

A modification of the Harris program, called RADCON, added a refinement which accounted for thermal conductivity being a function of temperature. RADCON includes an iterative loop which updates the thermal conductivity used so it is the correct value for the average temperature calculated for ^ gas. RADCON is listed in Appendix A.

The results of the program are plotted in Figures 2 and 3 for fi ; helium and argon. The maximum pin temperature is plotted as a fi assembly thermal power with the temperature of the shell as a paramet

Heat Transfer Analysis: Hexagonal Shell to Heat Sink

In the second stage of the heat transfer process, heat was transferred from the hexagonal shell of the fuel assembly to the basket structure by thermal radiation and either conduction or free convection in the filler gas. Tests in an electrically heated mockup of a hexagonal shell inside a tube at Oak Ridge showed that 25% of the heat generated in the active region is dissipated in the axial direction. Therefore, this thermal analysis considered only 75% of the total heat output to be flowing radially.

Thermal Radiation

The thermal radiation problem was solved by arbitrarily dividing the entire surface area involved in radiative heat transfer into six discrete surfaces which are labeled in Figure 4. The radiant heat transfer process is illustrated schematically in Figure 5 using an electrical analog suggested by Kreith[2]. The numbers one through six on Figure 5 refer to corresponding surfaces marked in Figure 4. The resistances on the schematic correspond to the resistance to the flow of radiation energy between two surfaces. This analysis for radiant heat transfer requires the assumption that each discrete surface is at a constant and uniform temperature. In the figure, E_{Bi} is the black body emissive power for surface i, where:

$E_{Bi} = \sigma T_i^4$

T_i = temperature (^oR) of surface i

σ = Stefan-Boltzmann constant = 0.1714×10^{-8} Btu/ft^2/hr/$^oR^4$

A_i = area of surface i

ε_i = emissivity of surface i

ρ_i = $1-\varepsilon_i$ = reflectivity of surface i

F_{i-j} = radiation shape factor for energy flow from surface i to surface j

Q_i = net energy flow to or from surface i

E_{B1} is a known quantity because T_1, the temperature of the heat sink, is specified. Using the electrical analogy, equations were derived for the heat transfer rates Q_1 and Q_2 in terms of other variables. Because the unknown quantities are E_{B2} and E_{B3}, the equations were rearranged to give:

$$E_{B2}\,F_{1-2} + E_{B3}\,F_{1-3} = C$$

$$E_{B2}\,(F_{2-1} + F_{2-3}) - E_{B3}\,F_{2-3} = D$$

where:

$$C = \frac{Q_1}{A_1} + E_{B1} + \frac{Q_1\rho_1}{A_1\varepsilon_1}\,(F_{1-2} + F_{1-3}) + \frac{Q_2\rho_2}{A_2\varepsilon_2}\,F_{1-2} + \frac{Q_3\rho_3}{A_3\varepsilon_3}\,F_{1-3}$$

$$D = \frac{Q_2}{A_2} + E_{B1} + \frac{Q_1\rho_1}{A_1\varepsilon_1}\,F_{2-1} + \frac{Q_2\rho_2}{A_2\varepsilon_2}\,(F_{2-1} + F_{2-3}) - \frac{Q_3\rho_3}{A_3\varepsilon_3}\,F_{2-3}$$

For segments of the inner ring of the basket an expression for Q_6 was derived.

$$Q_6 = A_6\,\sigma\,(T_6^{\,4} - T_4^{\,4})\,\mathcal{F}_{6-4}$$

$$\text{where } \mathcal{F}_{6-4} = \left[\frac{\rho_6}{\varepsilon_6 A_6} + \frac{\rho_4}{\varepsilon_6 A_6} + \frac{1}{A_6\left[F_{6-4} + \dfrac{1}{\dfrac{1}{F_{6-5}} + \dfrac{A_6}{A_4 F_{4-5}}}\right]}\right]^{-1}$$

The radiation shape factors were found graphically using Hottel's crossed string rule which is described in Siegel and Howell(3). The computed values of the shape factors along with the areas and assumed emissivities of the surfaces are listed in Table 1.

From Figure 5, it may be seen that $Q_4 = Q_6$. Also, heat flows Q_2 and Q_4 pass through the same boundary. The following equation is true because there are six fuel assemblies on one side of the boundary and fourteen on the other.

$$Q_2 = \frac{6}{14}\,Q_6$$

Free Convection

Heat is also transferred by free convection or, for the bottom assembly in a horizontal cask, by conduction through the filler gas. The geometry for the free convection problem is complex. The simplifying assumption was made that the heat transfer coefficient between the fuel assembly and the basket is the same as for the hypothetical pairs of parallel plates marked

A, B and C in Figure 6. The members of the pairs of plates in the figure are not equal in width. It was further assumed that the equivalent width was equal to the numerical average of widths for each pair. The heated portion of the fuel assembly is three feet long. The areas for convective heat transfer are:

$$A_A = 1.81 \text{ ft}^2$$

$$A_B = 1.38 \text{ ft}^2$$

$$A_C = 1.75 \text{ ft}^2$$

When the cask is vertical, the assumed parallel plates are also vertical. A correlation for the convective heat transfer in air was taken from Eckert and Carlson[4]. It should also apply to helium and argon which have nearly the same Prandtl numbers as air.

$$Nu_H = 0.119\ Gr_H^{0.3}$$

where $Gr_H = \dfrac{H^3 g_c\ \beta\ \Delta T}{\nu^2}$ and $Nu_H = \dfrac{h}{Hk}$

H = plate height (ft)

β = coefficient of expansion, equals 1/T for ideal gas ($^oR^{-1}$)

ν = kinematic viscosity (lb_m/ft hr)

g_c = 4.18×10^8 ft/hr^2

h = heat transfer coefficient (Btu/ft^2/^{o}R/hr)

k = thermal conductivity of filler gas (Btu/ft/^{o}R/hr)

When the cask is horizontal, the assumed parallel plates may be horizontal or at some angle to the horizontal plane. A correlation for the heat transfer in this case was taken from Dropkin and Somerscales[5].

$$Nu_L = 0.069\ (Gr_L \cdot Pr)^{1/3} \cdot Pr^{0.074}$$

where L = plate separation (ft).

If the cask is horizontal, no credit can be taken for free convection for the bottom segment of the basket because for that segment the hot surface is directly above the cold surface. Using the assumption of a parallel plate geometry, the heat transfer coefficient is: $h = k/L$

The two filler gases used in the analyses were argon and helium. Tables of the properties of helium and argon were found in Kreith[2] and Bolz and Tuve[6], respectively. The data were correlated by the following equations:

Helium at 4 Atmospheres:

$$\frac{g_c \beta}{\nu^2} = 2.82 \times 10^{17} T^{-4.276}$$

$$k = 3.05 \times 10^{-3} T^{.533}$$

Argon at One Atmosphere:

$$\frac{g_c \beta}{\nu^2} = 6.52 \times 10^{18} T^{-4.54}$$

$$k = 6.54 \times 10^{-5} T^{.801}$$

The electrical analogy was used again to include the additional heat transfer by convection or conduction in the filler gas. Figure 7 is a modification of Figure 5 showing the additional pathways for heat transfer. The three additional heat flows are:

$$Q_A = h_A A_A (T_3 - T_1)$$

$$Q_B = h_B A_B (T_3 - T_2)$$

$$Q_C = h_C A_C (T_6 - T_4)$$

When equations are written for the total heat transfer rates by both radiation and convection for Q_1 and Q_2, the resulting equations reduce to:

$$\sigma T_2^4 F_{1-2} + \sigma T_3^4 F_{1-3} + \frac{A_A}{A_1} h_A (T_3 - T_1) = C \quad (1)$$

$$\sigma T_2^4 (F_{2-1} + F_{2-3}) - \sigma T_3^4 F_{2-3} - \frac{A_B h_B}{A_2} (T_3 - T_2) = D \quad (2)$$

where C and D were defined previously.

For the inner circle of fuel assemblies the total heat transfer rate for both radiation and conduction or convection is

$$Q_6 = A_6 \mathcal{F}_{6-4} \sigma (T_6^4 - T_4^4) + A_C h_C (T_6 - T_4) \quad (3)$$

Solution Algorithm

The goal was to calculate the maximum pin temperatures in the fuel assemblies as a function of assembly power levels Q_3 and Q_6. The first half of the solution was to calculate the temperatures of the hexagonal shells in the outer and inner rings, T_3 and T_6. The heat transfer rates are related by

$$Q_2 = \frac{6}{14} Q_6$$

$$Q_1 = Q_2 + Q_3$$

The heat sink temperature T_1 is specified as input data. T_2 equals T_4 because they are measured at a common boundary.

A computer algorithm having the following steps was developed to solve equations (1), (2) and (3) simultaneously for T_2, T_3 and T_6. This program, CASK, is listed in Appendix B.

1. Using an initial guess of T_3 equation (1) is solved for T_2.

2. Using the same initial guess for T_3 equation (2) is solved for T_2 using Newton's method.

3. Because the value for T_3 was a guess the two values calculated for T_2 will disagree.

4. Using Newton's method new values of T_3 are chosen so that the difference between the two calculated values of T_2 decreases below an acceptable error level.

5. T_4 equals T_2. Equation (3) is solved for T_6 using Newton's method.

6. T_6 and T_3 are the desired quantities.

The second half of the solution was to find the maximum pin temperatures for the assemblies in the inner and outer rows. For a given power level the hexagonal shell temperature was calculated using the preceding analysis. Then either Figure 2 or 3, depending on the gas, was interpolated to find the maximum fuel pin temperature.

The results are shown in Figures 8, 9 and 10. Five curves are plotted in each graph. The first is the maximum pin temperature for fuel assemblies in the outer circle when there are no fuel assemblies in the inner circle. The second and third are the maximum pin temperatures for assemblies in the inner circle as a function of inner circle assembly power. For the second curve the outer circle assembly power is 1.4 kw while for the third it is 2 kw. The fourth and fifth curves are the maximum pin temperatures in the outer circle assemblies as a function of the inner circle assembly power. For the fourth the outer circle assembly power is 1.4 kw while for the fifth it is 2 kw.

Conclusions

1. The maximum pin temperature in a fuel assembly is strongly dependent on the power output of that assembly.

2. The maximum pin temperature in an assembly is only weakly dependent on the power output of the assemblies in the other circle of assemblies.

3. For a given power output, the fuel pins will be hottest when the cask is vertical and filled with argon.

4. When the cask is horizontal and filled with helium, free convection is only slightly more effective than conduction for cooling. As a result the fuel pins at the top of the cask are at approximately the same temperature as those on the bottom.

JLS/eh

REFERENCES

1. J. P. Morin, *Thermal Analysis of Planned Storage of FFTF Fuel Assemblies*, DPST 73-386.

2. Frank Kreith, *Principles of Heat Transfer*, International Textbook Co. (1969).

3. Robert Siegel and John R. Howell, *Thermal Radiation Heat Transfer*, McGraw-Hill (1972).

4. E. R. G. Eckert and Walter O. Carlson, *Natural Convection in an Air Layer Enclosed Between Two Vertical Plates with Different Temperatures*, Int. J. Heat Mass Transfer, 2 106 (1961).

5. D. Dropkin and E. Somerscales, *Heat Transfer by Natural Convection in Liquids Confined by Two Parallel Plates Which are Inclined at Various Angles with Respect to the Horizontal*, J. Heat Transfer p.1 (1964).

6. R. E. Bolz and T. L. Tuve, ed., *Handbook of Tables for Applied Engineering Science*, Second edition, CRC press (1970).

Figure 1 Half Cross Section of NL 10/24
Shipping Cask Basket

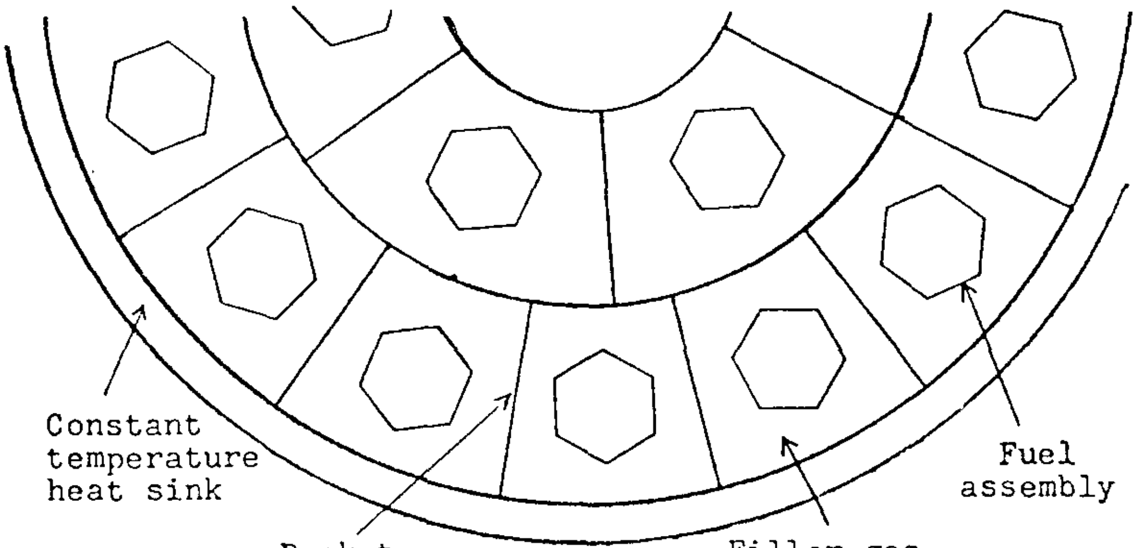


FIGURE 2

Pin Temperatures in Helium

Note:
1. All gamma radiation was assumed to be converted to heat inside the pins.
2. This is for pin temperature vs. assembly power with hexagonal shell temperature as a parameter.

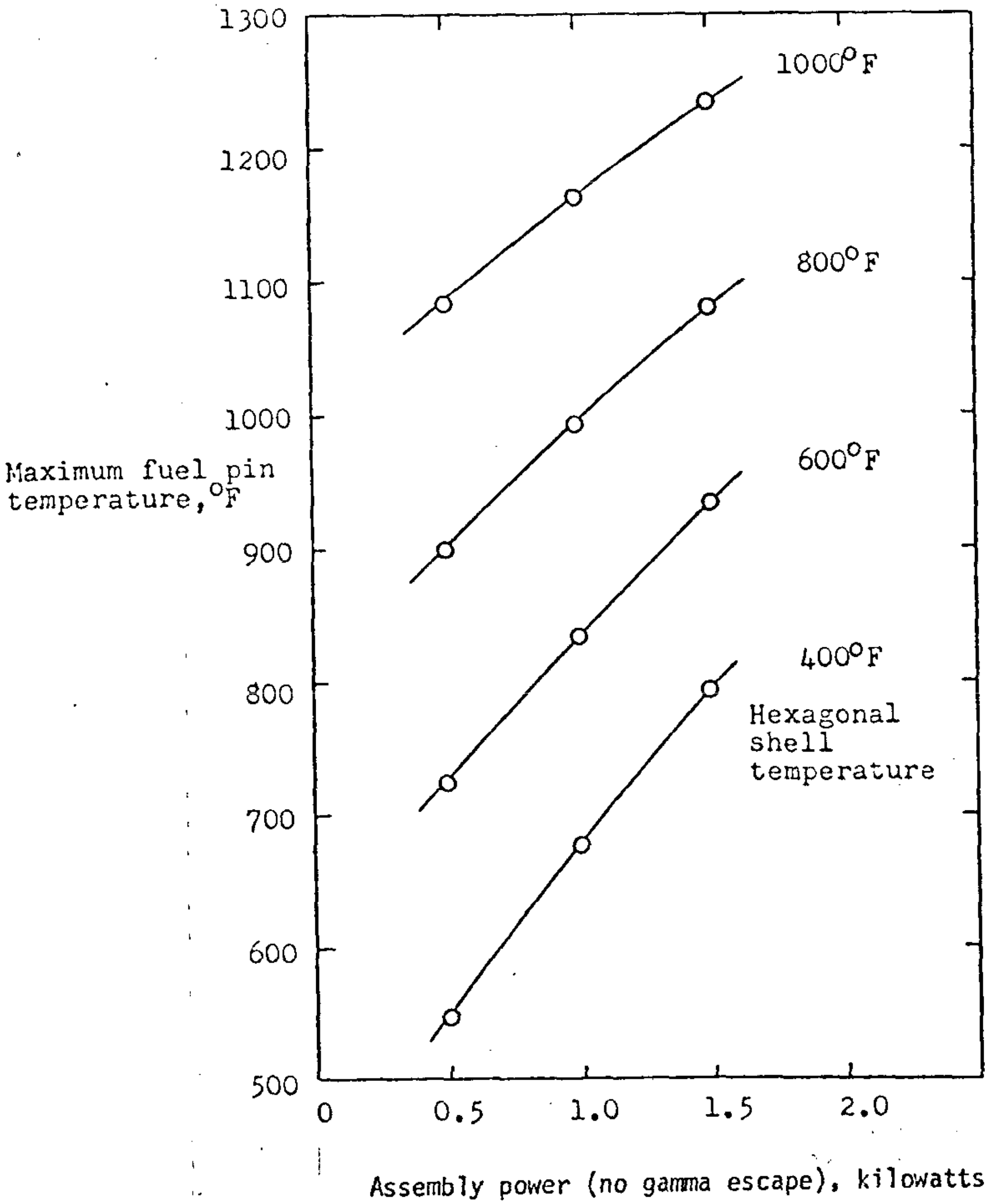


FIGURE 3

Pin Temperatures in Argon

Note: 1. All gamma radiation was assumed to be converted to heat inside the pins.

2. This is for pin temperature vs. assembly power with hexagonal shell temperature as a parameter.

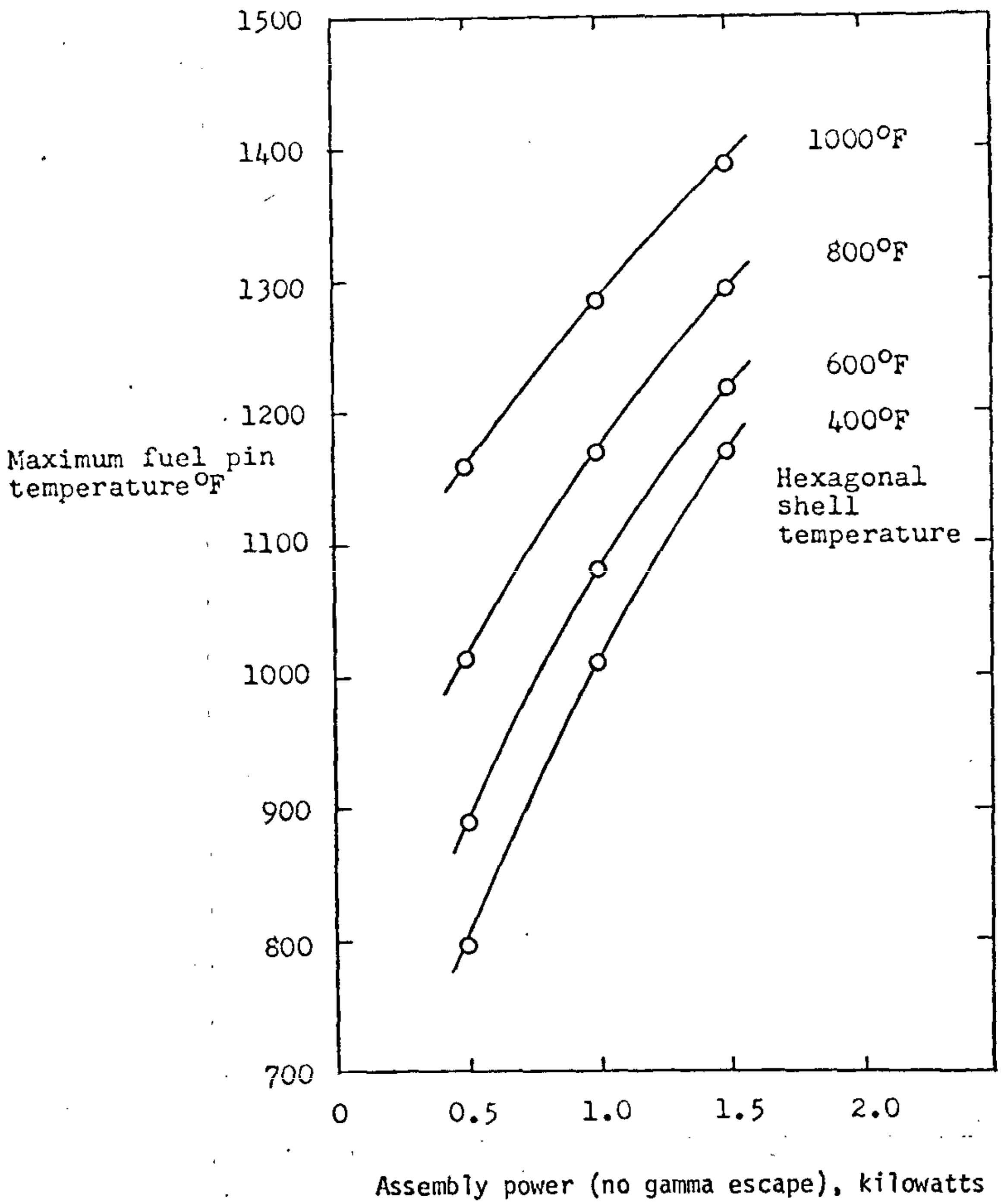


Figure 4 Surfaces Involved in Radiation Heat Transfer

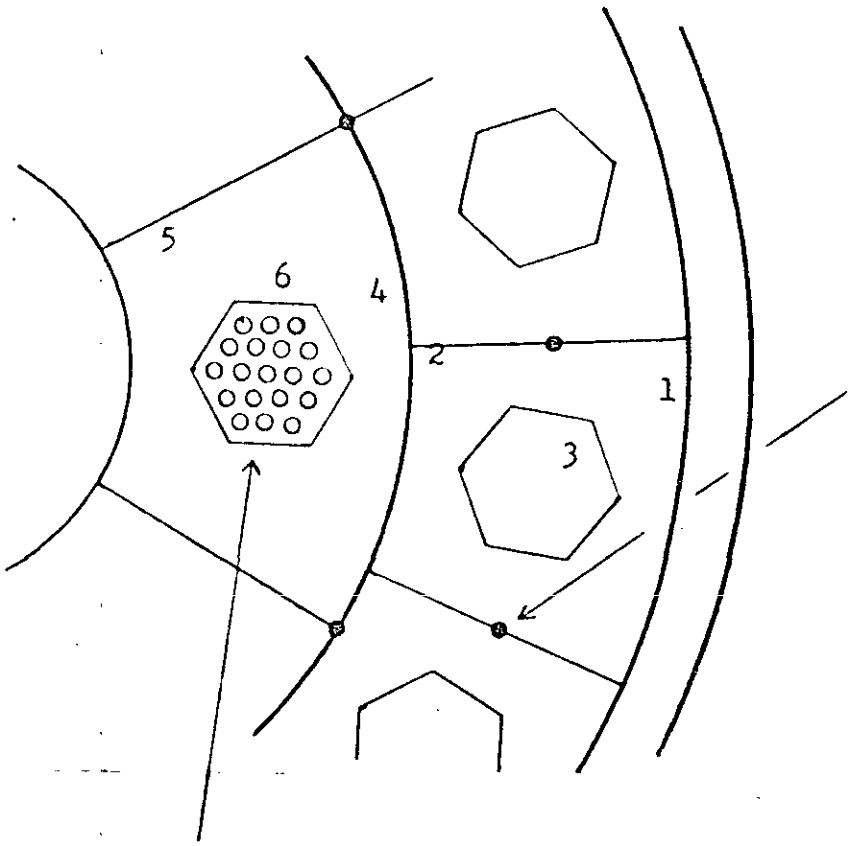
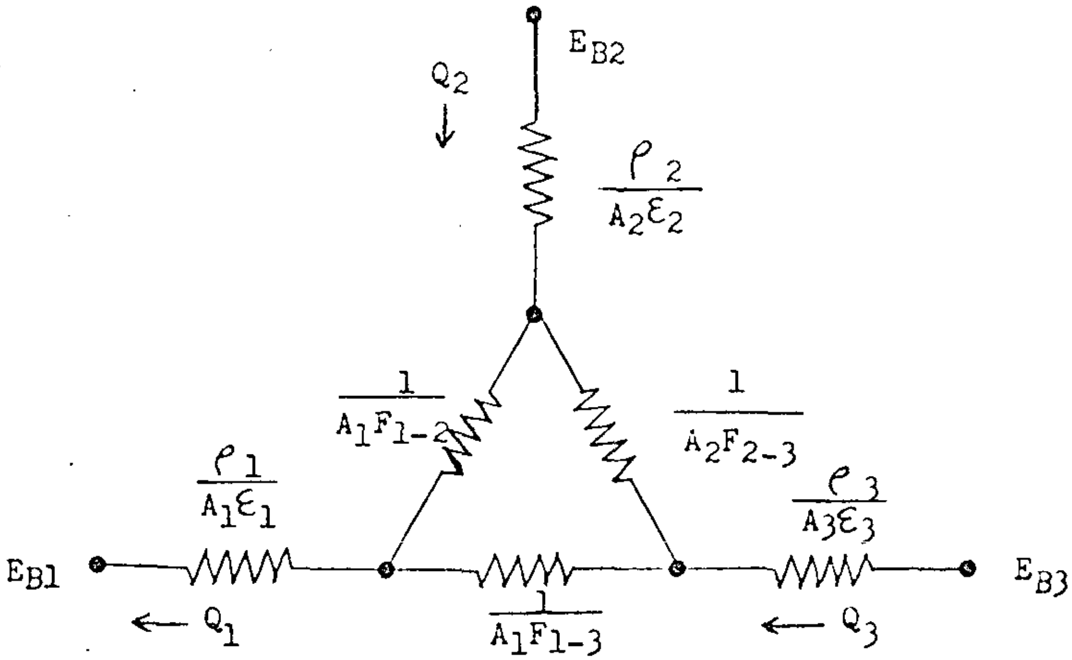


FIGURE 5

Schematic of Radiant Heat Transfer

Segment in Outer Ring of Basket



Segment in Inner Ring of Basket

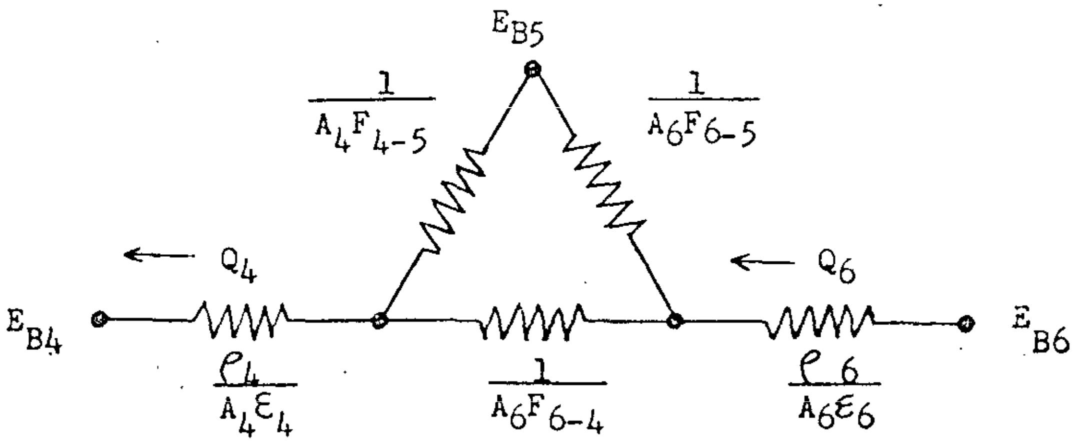
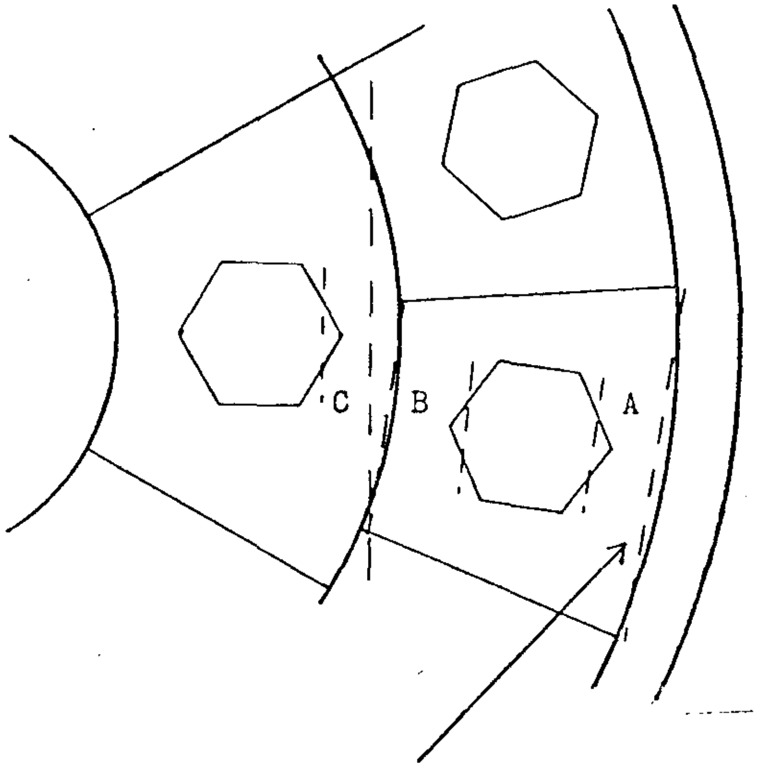


Figure 6 Hypothetical Parallel Plates Used for Free Convection



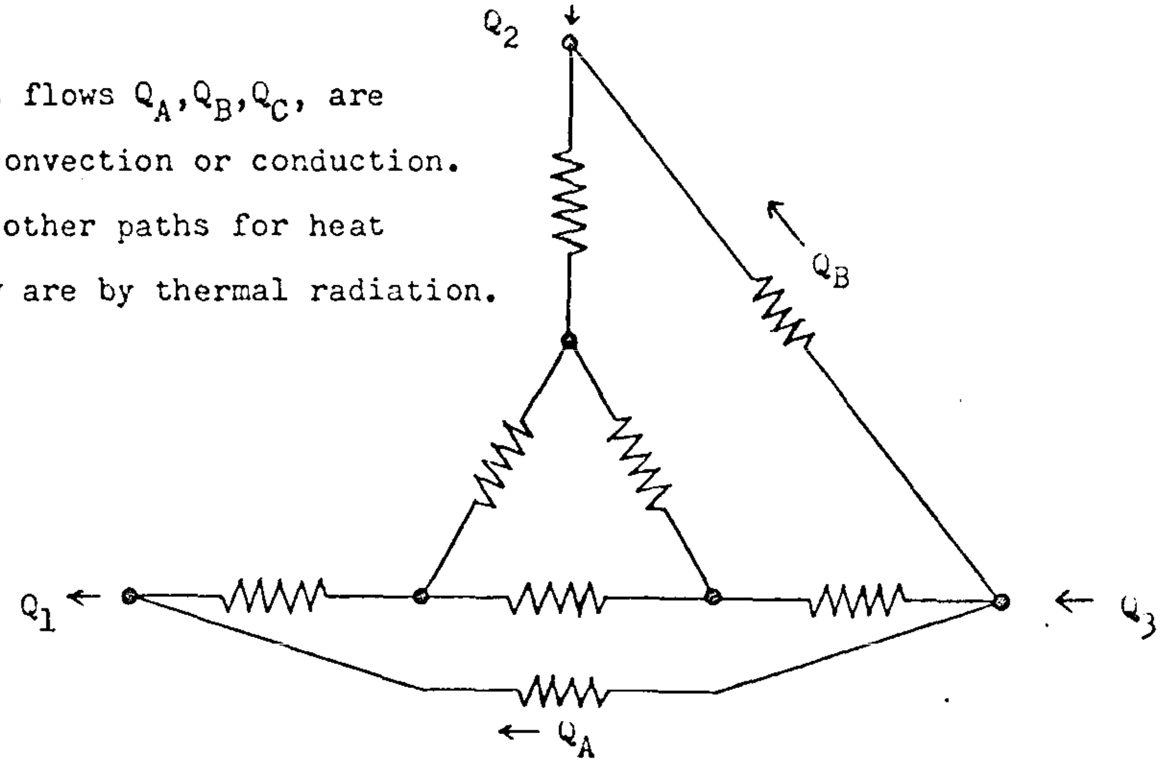
The three pairs of plates are marked by dashed lines and labelled with letters.

FIGURE 7

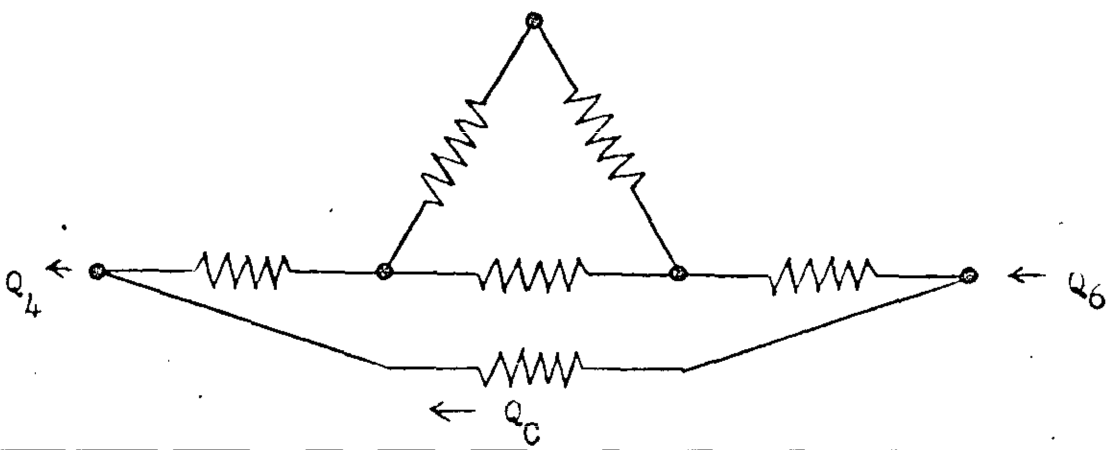
Schematic of Radiant and Convective or Conductive Heat Transfer

Segment in Outer Ring of Basket

Heat flows Q_A, Q_B, Q_C, are by convection or conduction. The other paths for heat flow are by thermal radiation.

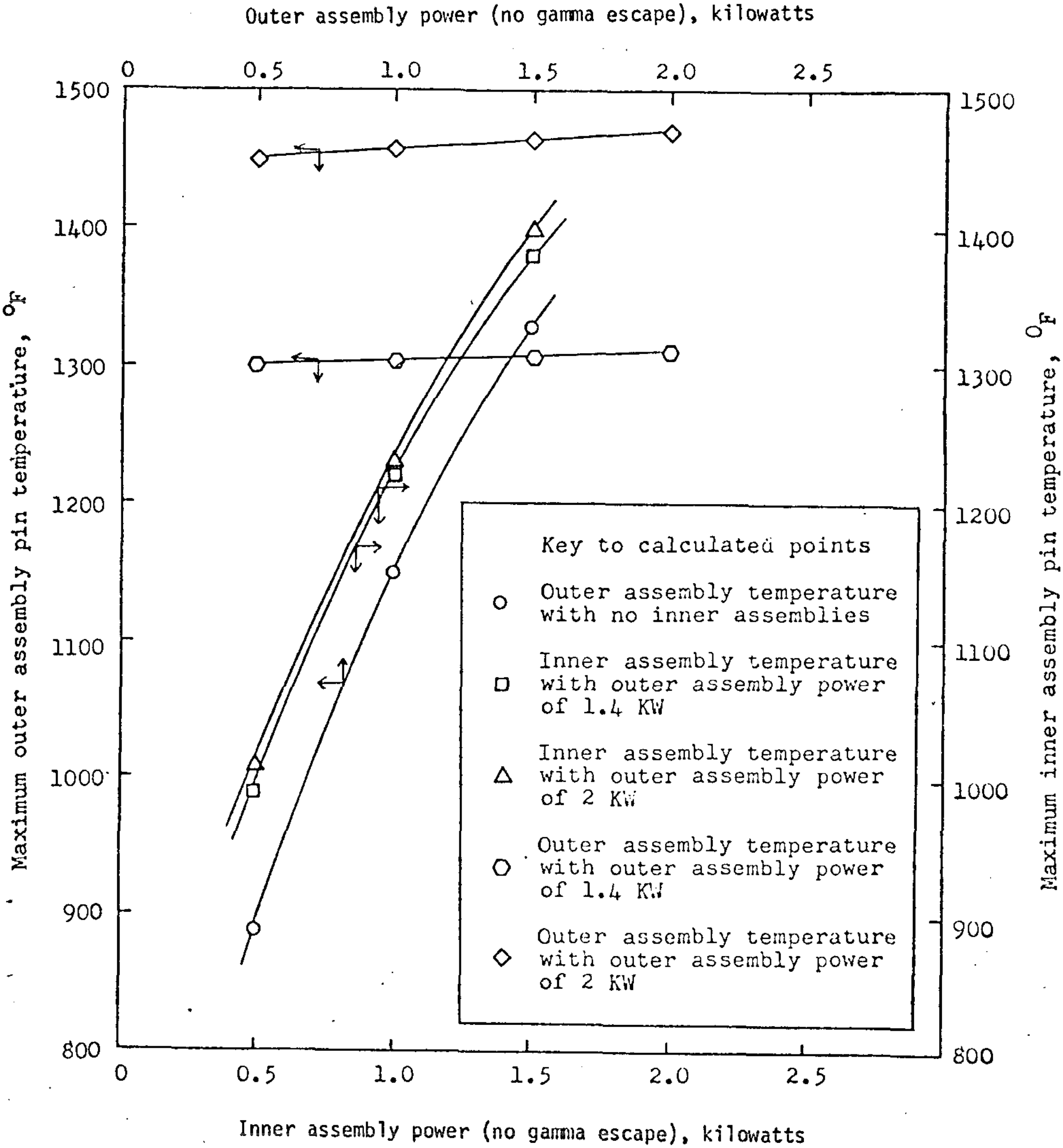


Segment in Inner Ring of Basket



Maximum Pin Temperatures as a Function of Assembly Power-
Vertical Cask Filled With Argon

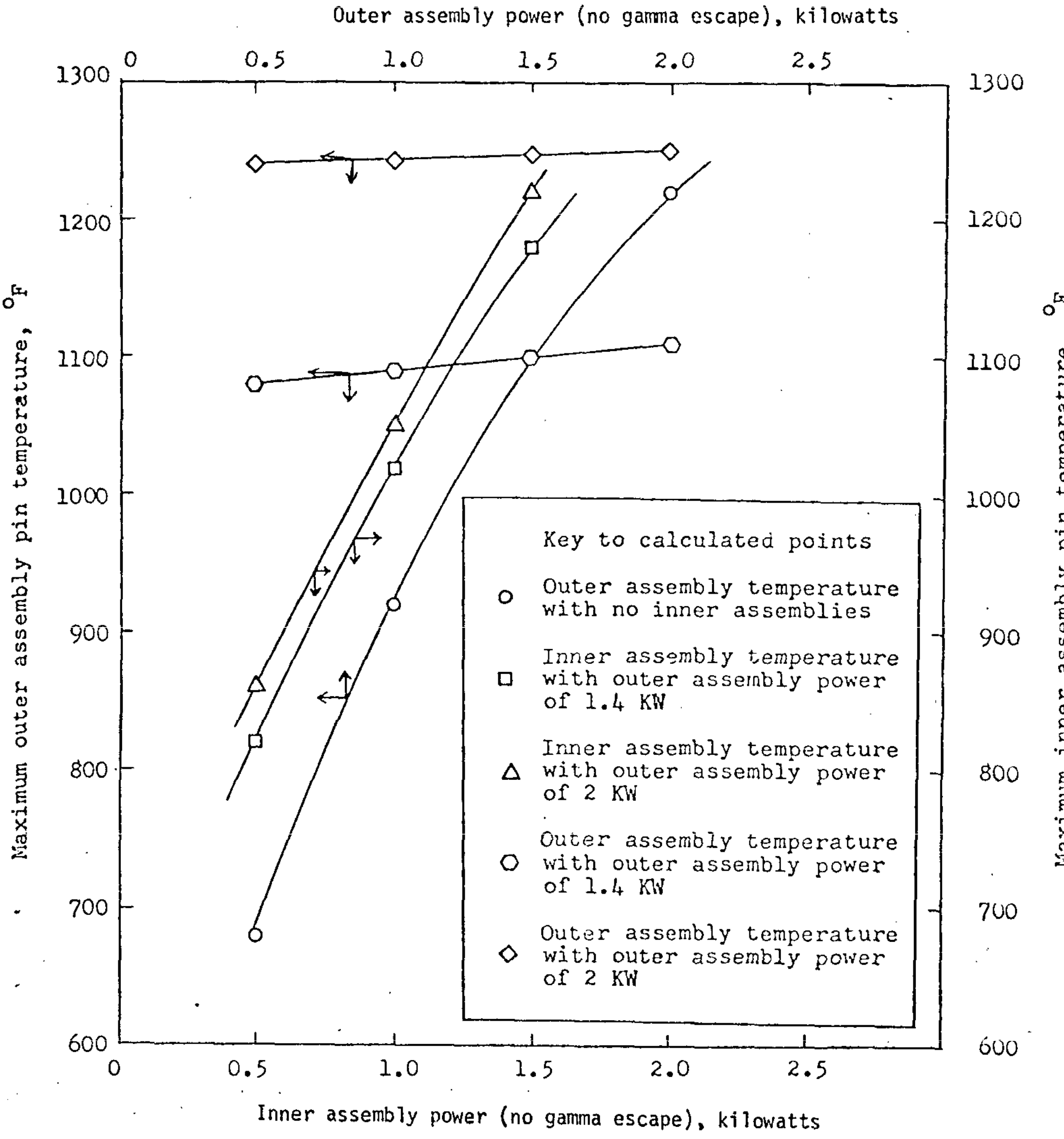
Note: All gamma radiation was assumed to be converted to heat inside the pins.



Maximum Pin Temperatures as a Function of Assembly Power-

Horizontal Cask Filled With Helium

Note: All gamma radiation was assumed to be converted to heat inside the pins.



Maximum Pin Temperatures as a Function of Assembly Power-Horizontal Cask Filled with Helium, Convection Not Considered

Note: All gamma radiation was assumed to be converted to heat inside the pins.

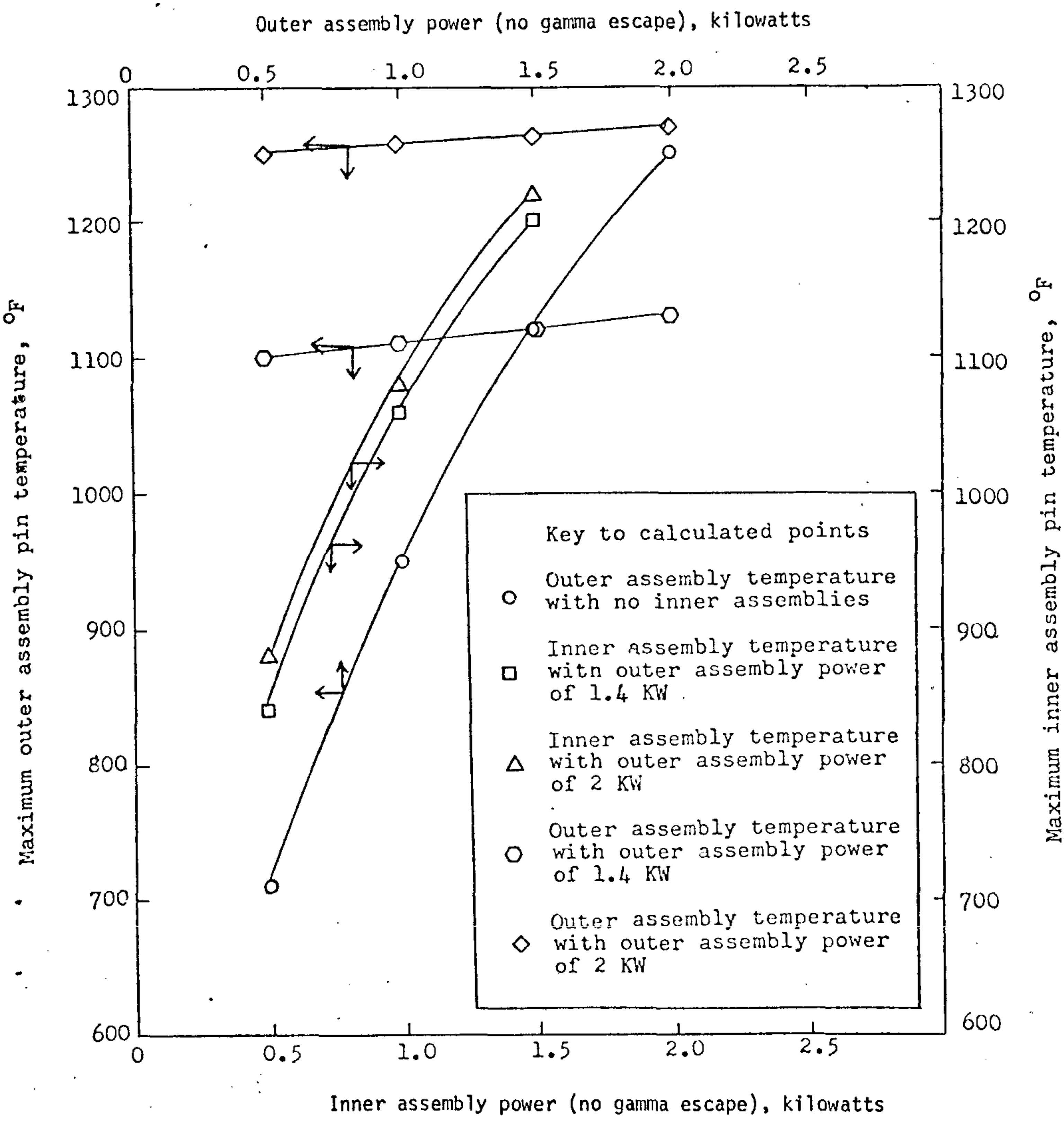


TABLE I. Shape Factors, Areas and Emissivities

Shape Factors:

$F_{1-3} = 0.492$	$F_{6-4} = 0.4$
$F_{2-3} = 0.50$	$F_{6-5} = 0.6$
$F_{1-2} = 0.15$	$F_{4-5} = 0.548$
$F_{2-1} = 0.163$	

Areas: (ft^2)

$A_1 = 3.94$	$A_4 = 3.88$
$A_2 = 3.63$	$A_5 = 6.13$
$A_3 = 3.75$	$A_6 = 3.94$

Assumed Emissivities:

$\varepsilon_1 = 0.85$	$\varepsilon_4 = 0.8$
$\varepsilon_2 = 0.80$	$\varepsilon_5 = 0.8$
$\varepsilon_3 = 0.25$	$\varepsilon_6 = 0.25$

APPENDIX A - RADCON PROGRAM

The program RADCON calculates the maximum fuel pin temperature in a breeder reactor fuel assembly as a function of the power level and the shell temperature. A listing follows.

```
C     PROGRAM  RADCON
C          CALCULATION CF PIN CLACDING TEMPS FOR LMFBR ASSEMBLY
C            ASSUMES: GAS   INSIDE AROUND PINS
C                     NC ALLOWANCE FOR ABSCRPTIVITY OF GAS
C                     ARBITRARY PASS THROUGH FACTOR
C                     RADIATICN AND CONDUCTION CONSIDERED, BUT NOT CONVECTIO
       DIMENSION A1(10),D(9),ABR(9),AF(9),PRAD(9),RMKS(18),A2(8),
      1QRAD(9),T(10),TF(1C)
C          GEOMETRICAL CATA
       DATA A1/.625,.752,.662,.572,.482,.391,.301,.211,.120,.030/
       DATA A2/.692,.602,.512,.421,.331,.241,.151,.06/
       DATA D/9*.14/
       DATA ABR/.689,.677,.587,.497,.406,.316,.226,.136,.045/
       DATAPRAD/28.13,21.13,15.13,10.13,6.13,3.13,1.13,.133,0./
       DATAQRAD/8.,7.,6.,5.,4.,3.,2.,1.,.167/
       DO 2 I=1,9
     2 D(I)=D(I)/12.
C         READ IN PROBLEM TITLE
     1 READ(5,100,END=500)RMKS
       WRITE(6,101)RMKS
       READ(5,102)PTOT,RODS,DROD,HTLGTH
C               PTOT=ASEMBLY PCWER, KW
C               RODS=NUMBER OF RODS PER ASSEMBLY
C               DROD=ROD DIAMETER, INCHES
C               HTLGTH=HEATED LENGTH OF ASSEMBLY, INCHES
       WRITE(6,103)PTOT,RODS,DROD,HTLGTH
       READ(5,102)TFCASK,HDUCT,CONSTL,TDUCT,SHROUD
C           TFCASK=TEMP OF WATER IN CASK, F
C            HDUCT=H.T. COEFFICIENT OF OUTER DUCT SURFACE
C            CONSTL=CCNDUCTIVITY CF STEEL
C            TDUCT=WALL THICKNESS OF SHROUD,INCHES
C            SHROUD=OUTER HEATED SURFACE AREA OF SHROUD OR DUCT, IN**2
       WRITE(6,103)TFCASK,HDUCT,CONSTL,TDUCT,SHROUD
       READ(5,102) T10,  EMISS,RPASS
C          T10=FIRST GUESS FCR T(10)
C          EMISS=EMISSIVITY OF RCDS
C          RPASS=FRACTION OF ROD RADIATION ESCAPING DIRECTLY
C
       WRITE(6,103) T10,  EMISS,RPASS
C          ADJUST UNITS
```

```
      DROD=DROD/12.
      PTOT=PTOT*3413.
      HTLGTH=HTLGTH/12.
      TCASK=TFCASK+460.
      TDUCT=TDUCT/12.
      SHROUD=SHROUD/144.
      PINHT=PTOT/RODS
      SIGMA=0.1712E-08
C          PIN SURFACE HEAT FLUX
      AREA=3.14159*DROD*HTLGTH
      PFLUX=PINHT/AREA
C          VOLUMETRIC GENERATION RATE
      VOL=.7854*DROD*DROD*HTLGTH
      QVOL=PINHT/VOL
      KK=0
C   CALCULATE TOTAL CONDUCTANCE FOR EACH ROW
      DO 5 I=1,9
      IF(I.EQ.1)GOTO4
      AF(I)=1./(A1(I+1)*EMISS)+(1./A2(I-1))*(1./EMISS-1.)
      GO TO 5
    4 AF(I)=1./(A1(I+1)*EMISS)+(1./A1(I))*(1./EMISS-1.)
    5 AF(I)=1./AF(I)
      WRITE(6,104)(I,AF(I),I=1,9)
      FLUX=PTOT/SHROUD
      WRITE(6,107)PFLUX,FLUX,QVOL
C          INSIDE SHROUD WALL TEMP
      UA=1./(1./(HDUCT*SHROUD)+TDUCT/(SHROUD*CONSTL))
      T(1)=TCASK+PTOT/UA
   20 KK=KK+1
      TBULK=(TCASK+T10)/2.
C   THERMAL CONDUCTIVITY FOR ARGON
      CONGAS=6.54E-5*TBULK**.801
      WRITE(6,110) KK,CONGAS
  110 FORMAT(' KK=',I2,'   GAS THERMAL CONDUCTIVITY =',E10.3)
C
C             CALCULATE ROW TEMPS STEP BY STEP  (USING 1/6 OF ASSEMBLY)
```

```
      DO 10 I=2,10
      J=I-1
      Q=QRAD(J)*PINHT+(1.-RPASS)*PRAD(J)*PINHT
C           I'S COUNT TEMPS WHERE WALL=1.  J'S COUNT ROWS, WHERE OUTER=1
C           EACH LOOP SLVES FOR T(I)=T(J+1), THE CURRENT ROW CLADDING TEMP
      C1=SIGMA*AF(J)
      C2=CONGAS*ABR(J)/D(J)
      C3=-(Q+C1*T(I-1)**4+C2*T(I-1))
      TOLD=1000.
      CALLSOLVE(C1,C2,C3,TCLD,T(I))
      WRITE(6,109)J,Q,C1,C2,C3
   10 CONTINUE
      TF(1)=T(1)-460.
      WRITE(6,105) TF(1)
      WRITE(6,106)
      DO 15 I=2,10
      TF(I)=T(I)-460.
      J=I-1
   15 WRITE(6,108)J,TF(I)
      E=ABS(T(10)-T10)
      IF(KK .EQ. 10 .CR. E .LT. 1.) GO TC 1
      T10=T(10)
      GO TO 20
  500 STOP
  100 FORMAT(18A4)
  101 FORMAT('1',18A4/' CATA REPEAT')
  102 FORMAT(7F10.0)
  103 FORMAT(1X,5F12.4)
  104 FORMAT(' TOTAL CCNDUCTANCES FOR EACH ROW'/(1X,I5,F12.3))
  105 FORMAT(' CALCULATED INNER WALL TEP=',F10.2,' F')
  106 FORMAT(' ROW TEMPS, CUTER TO CENTER=')
  107 FORMAT(' PIN SURFACE HEAT FLUX=',F10.0/1X,'SHROUD SURFACE HEAT FLU
     1X=',F10.0/1X,'PIN VOLUMETRIC GENERATICN=',F12.0/'ONUM. INFO:')
  108 FORMAT(1X,I5,F12.3,' F')
  109 FORMAT(1X,I5,4E12.5)
      END
```

```
      SUBROUTINE SOLVE(C1,C2,C3,TOLD,T)
C        SOLVES THE 4TH ORDER RADIATION/CONDUCTION POLYNOMIAL BY NEWTONS ME
      KOUNT=0
      T=TOLD
    2 KOUNT=KOUNT+1
      IF(KOUNT.GT.10000)GO TO 5
      A=C1*T*T*T*T
      B=C2*T
      C=C3
      FT=A+B+C
      F1T=(4.*A+B)/T
      T=T-FT/F1T
      IF(ABS((T-TOLD)/T).LE..001)RETURN
      TOLD=T
      IF(T.GT.10000..CR.T.LT.0.)GOTO5
      GO TO 2
    5 CONTINUE
      WRITE(6,100)C1,C2,C3,T,KCUNT
  100 FORMAT('OGOOF IN SCLVE.',4E12.4,I6)
      RETURN
      END
```

APPENDIX B - CASK PROGRAM

The program CASK calculates the temperature of the fuel assembly shell as a function of power level. A listing follows.

```
C    PROGRAM CASK
C    CALCULATE TEMPERATURES IN THE NL 10/24 CASK CONSIDERING BOTH THERMAL
C    RADIATION AND FREE CONVECTION
C    CASK HAS HCRIZONTAL ORIENTATION  HELIUM GAS AT 4 ATM.
C    FOR TOP ASSEMBLY CONSIDER FREE CONVECTICN BETWEEN TWO HORIZONTAL
C    PARALLEL PLATES
C    USES NEWTONS METHOD TO SOLVE EQUATIONS
C    DATA:  SUPPLY HEAT FLLXES, CUTER WALL TEMP AND GUESS OTHER TEMPS
C    UNITS:  Q KILOWATTS    T DEGREES R.
      DIMENSION T3(30),E(30),T6(30)
      DO 80 M=1,12
      SG=.1714E-8
      READ(5,55) FR,Q3,Q6,T1,T2,T3(1)
   55 FORMAT(6F10.0)
      WRITE(6,59) M,FR,Q3,Q6,T1,T2,T3(1)
   59 FORMAT(///,' DATA SET NUMBER ',I2,/,' FRAC. ENERGY RADIAL=',
     *F4.2,'   Q3,Q6= ',2F10.3,/,' T1 AND GUESSES T2,T3=',3F10.0/)
C    CHANGE UNITS OF Q TC BTU PER HOUR
      Q3=3410.*Q3*FR
      Q6=3410.*Q6*FR
      Q2=6./14.*Q6
      Q1=Q2+Q3
      E1=SG*T1**4
      C=.283*Q1+.0103*Q2+.394*Q3+.642*E1
      D=.0073*Q1+.321*Q2-.4*Q3+.163*E1
      I=0
    7 I=I+1
C    START ITERATION WITH FIRST GUESS OF T3
      Z=T3(I)
      DT=Z-T1
      H=C-.492*SG*Z**4-55.1*ABS(DT)**1.333/(T1+DT/2.)**.892
      IF(H .GT. 0.) GC TO 44
      T2A=T1+10.
      GC TO 45
   44 T2A=(H/.15/SG)**.25
   45 CALL SOLVE(Z,T2,T2B,D)
      E(I)=T2A-T2B
```

```
      IF(I .GE. 2) GO TO 10
      T3(2)=1.01*T3(1)
      GO TO 7
   10 EE=E(I-1)-E(I)
      IF(EE .NE. 0.) GO TO 11
      T3(I+1)=T3(I)
      GO TO 52
   11 T3(I+1)=T3(I)-E(I)*(T3(I-1)-T3(I))/EE
      IF(T3(I+1) .LT. 0.) T3(I+1)=0.
      IF(I .EQ. 20) GO TO 12
      IF(ABS(E(I)) .GT. 1.) GO TO 7
      GO TO 52
   12 WRITE(6,50)
   50 FORMAT(' CONVERGENCE FOR T3 FAILED')
   52 WRITE(6,51) T3(I+1),T2B,I,E(I)
   51 FORMAT(' T3=',F8.0,'  T2=',F8.0,'  I=',I2,'  E=',E8.2)
C   CALCULATE T6 STARTING WITH APPROXIMATE VALUE
      T6(1)=(Q6/SG/.212/3.94+T2B**4)**.25
      J=0
   30 J=J+1
      DT=T6(J)-T2B
      E(J)=Q6-3.94*.212*SG*(T6(J)**4-T2B**4)-210.*ABS(DT)**1.333
     */(T2B+DT/2.)**.892
      IF(J .GE. 2) GO TO 31
      T6(2)=1.01*T6(1)
      GO TO 30
   31 EE=E(J-1)-E(J)
      IF(EE .NE. 0.) GO TO 37
      T6(J+1)=T6(J)
      GO TO 33
   37 T6(J+1)=T6(J)-E(J)*(T6(J-1)-T6(J))/EE
      IF(T6(J+1) .LE. 0.) T6(J+1)=0.
      IF(J .EQ. 20) GO TO 32
      IF(ABS(E(J)) .GT. 10.) GO TO 30
      GO TO 33
   32 WRITE(6,54)
   54 FORMAT(' CONVERGENCE FOR T6 FAILED')
   33 WRITE(6,56) T6(J+1),E(J),J
   56 FORMAT(' T6=',F8.0,' E=',E8.2,'   J=',I2)
   80 CONTINUE
      END
```

```
      SUBROUTINE SOLVE(Z,T2,T2B,D)
      DIMENSICN T(30),E(30)
      SG=.1714E-8
      T(1)=T2
      K=0
    7 K=K+1
      DT=Z-T(K)
      E(K)=.663*SG*T(K)**4-.5*SG*Z**4-45.6*ABS(DT)**1.333/
     *(T(K)+DT/2.)**.892-D
      IF(K .GE. 2) GO TO 10
      T(2)=1.01*T(1)
      GO TO 7
   10 EE=E(K-1)-E(K)
      IF(EE .NE. 0.) GO TO 11
      T(K+1)=T(K)
      GO TO 12
   11 T(K+1)=T(K)-E(K)*(T(K-1)-T(K))/EE
      IF(T(K+1) .LT. 0.) T(K+1)=0.
      IF(K .EQ. 20) GC TC 15
      IF(ABS(E(K)) .GT. 1.) GO TO 7
      GC TO 12
   15 WRITE(6,50)
   50 FORMAT(' CONVERGENCE FOR T2 FAILED')
   12 WRITE(6,51) K,E(K),T(K+1)
   51 FORMAT('   K=',I2,'   ER=',E10.3,'   T2B=',E10.3)
      T2B=T(K+1)
      RETURN
      END
```