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SINTER - A PROGRAM FOR CALCULATING
RADIAL TEMPERATURE DISTRIBUTIONS
IN OXIDE FUEL PINS
UNDERGOING SINTERING

January 1970

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SINTER - A PROGRAM FOR CALCULATING RADIAL TEMPERATURE
DISTRIBUTIONS IN OXIDE FUEL PINS UNDERGOING SINTERING

by

K. R. Merckx

Metallurgy and Ceramics Department
Chemistry and Metallurgy Division

and

G. L. Fox

Reactor and Plant Technology Department
FFTF Division

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ABSTRACT

SINTER is a program for calculating the steady state radial temperature distribution within the fuel material of cylindrical fuel rods. The method uses the integral of the thermal conductivity over the temperature range which includes the temperature dependence for thermal conductivity. The fuel temperature distribution includes the effect of restructuring or sintering of the fuel material. The radius of the central void caused by such sintering is also calculated. This report reviews the theoretical basis of the procedure for calculating the temperature distributions and the geometrical changes.

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SINTER - A PROGRAM FOR CALCULATING RADIAL TEMPERATURE
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INTRODUCTION

SINTER is a program for calculating the radial temperature distribution within the fuel material of cylindrical fuel rods. This program takes into account the temperature dependence of the thermal conductivity and changes in density produced by the restructuring or sintering of the fuel material. The radius of the central void caused by such sintering is also calculated. The calculations described here were used as the basis for a previously completed but undocumented program called SINTR that calculated the effect of sintering along a fuel pin. SINTR employed at each axial node location the techniques described herein. This report reviews the theoretical basis of the procedure for calculating the temperature distributions and the geometrical changes.

DETERMINATION OF INPUT

The temperature calculations for the fuel material are based upon a description of the coolant flow conditions, the power generation within the fuel, and the initial geometry of the cladding and fuel material. The axial distribution of the power generation for SINTR is described by a chopped cosine curve where an extrapolation distance and the maximum power generation are used to describe this distribution. The coolant inlet temperature, mass flow rate, specific heat, and the prescribed power distribution are used to describe the coolant temperature condition at any axial location along the fuel pin. The temperature drops across the coolant film, the cladding, and the fuel gap interface are determined from the local linear heat generation rate and from the input values for the coolant film, gap conductances, and the thermal conductivity of the

cladding. The fuel surface temperature is determined by adding these temperature drops to the local coolant temperature.

The SINTER program applies a one-dimensional heat conduction theory- for the radial temperature distribution within the fuel material. The integral of the thermal conductivity over temperature as a function of the fraction of theoretical density* is given by:

$$T \leq 3272$$

$$S(T) = \frac{T^{0.613}}{(0.09084 - 0.07306 \times D)} - \frac{(54.615 \times D + 167.173)}{\exp(0.00154 \times T)}. \quad (1)$$

$$T > 3272$$

$$S(T) = S(3272) + 1.31769 \times (T - 3272)$$

where S = Integrated thermal conductivity [Btu/(hr × ft)]

T = Temperature (°F)

D = Fraction of theoretical density.

This equation applies for a material of constant density and should be used to calculate the changes in the integral value of the thermal conductivity from a reference temperature. The fraction of theoretical density before and after sintering are prescribed by the input. The temperature at which sintering occurs is also prescribed by the input. The geometry of the fuel material is described by its initial inner and outer radius (Figure 1).

TEMPERATURE PREDICTION WITHIN THE FUEL MATERIAL

The temperatures within the fuel material are assumed to be described by the heat conduction equation in terms of cylindrical coordinates. Axial symmetry and radial flow of the heat

* T. J. Bennett, "Incorporation of the Revised Thermal Conductivity and Integral KdT Curves into the FFTF Fuel Design Sintering Code" Internal PNL Letter, May 4, 1968.

FIGURE 1. *Schematic of Fuel Cross Section*

are assumed. The resultant equation for the temperature distribution, T , as a function of heat generation is

$$- \left[\frac{1}{r} \frac{d}{dr} r \left(K \frac{dT}{dr} \right) \right] = q(r), \text{ where} \quad (2)$$

q is the volumetric heat generation, and

K = the temperature dependent thermal conductivity.

Equation (2) may be integrated to obtain an expression for the heat flux as a function of radial position. The results of this integration are

$$- K \frac{dT}{dr} = \frac{1}{2\pi r} [Q_o - Q(r)], \text{ where} \quad (3)$$

$$Q_o = -2\pi R_o \left. K \frac{dT}{dr} \right|_{R_o} = \text{total linear heat generation, and}$$

$$Q(r) = 2\pi \int_r^{R_o} q x dx = \text{linear heat generation between } r \text{ and } R_o.$$

The total linear heat generation, Q_o , is defined by the axial power distribution, and the linear heat generation, $Q(r)$, is defined in terms of the volumetric heat generation.

Equation (3) is integrated to obtain

$$S(T) - S_o = \int_{T_o}^{T(r)} K dT = \frac{1}{2\pi} \int_r^{R_o} [Q_o - Q(x)] \frac{dx}{x}, \text{ where} \quad (4)$$

T_o = temperature at fuel surface, and

S_o = Integrated fuel conductivity at the fuel surface.

The numerical calculations assume the heat generation and density of the fuel material to be constant in an annular ring. The resultant heat generation in the ring $r < x < R_o$, and the integrated thermal conductivity are

$$Q(x) = \pi q (R_o^2 - x^2), \text{ and} \quad (5)$$

$$S(r) = S_o + \frac{\pi R_o^2 q}{4\pi} \left\{ 1 - \left(\frac{r}{R_o} \right)^2 + \left[1 - \frac{Q_o}{\pi R_o^2 q} \right] \ln \left(\frac{r}{R_o} \right)^2 \right\}.$$

For an annular pellet of constant density, the constant volumetric heat generation q , is

$$\pi R_o^2 q = \frac{Q_o}{\left[1 - \left(\frac{A_o}{R_o} \right)^2 \right]}, \text{ where} \quad (6)$$

R_o = outer radius

A_o = inner radius

and the relation for the integrated thermal conductivity is

$$S = S_o + \frac{Q_o}{4\pi \left[1 - \left(\frac{A_o}{R_o} \right)^2 \right]} \left\{ 1 - \left(\frac{r}{R_o} \right)^2 + \left(\frac{A_o}{R_o} \right)^2 \ln \left(\frac{r}{R_o} \right)^2 \right\}. \quad (7)$$

Equation (7) expresses the relation used to obtain the temperatures in the SINTER program. The values of S are calculated for the constant density ring and compared to the value S given by Equation (1). A table inversion procedure is used to obtain the temperature value.

The first temperature calculated is the maximum temperature, $T_{\max}$, in a fuel pellet not undergoing sintering. This temperature is used to determine whether center melting at start-up or sintering will occur. If sintering occurs, $T_{\max} > T_b$ - sintering temperature, Equation (7) can be solved for the sintering radius, R_b :

$$\left(\frac{R_b}{R_o}\right)^2 - \left(\frac{A_o}{R_o}\right)^2 \ln \left(\frac{R_b}{R_o}\right)^2 = 1 - \frac{4\pi \left[1 - \left(\frac{A_o}{R_o}\right)^2\right] (S_b - S_o)}{Q_o} \quad (8)$$

where S_b = integrated thermal conductivity at T_b for the unsintered density.

If the pellet is solid, then Equation (8) may be directly solved for R_b . A Newton approximation procedure is used to determine R_b for an annular pellet.

When sintering occurs, the density, inner dimensions, and heat generation in the sintered regions are altered. Conservation of mass is used to calculate the new inner radius A_s as follows:

$$D_u(R_b^2 - A_o^2) = D_s(R_b^2 - A_s^2), \text{ where} \quad (9)$$

D_u = relative fraction of theoretical density unsintered.

D_s = relative fraction of theoretical density sintered.

Equation (7) is used to determine the temperatures in the sintered region once the following substitutions are made:

$$S_o \rightarrow S_b = S(T_b) \text{ for } D_s,$$

$$Q_o \rightarrow Q_b = Q_o - Q(R_b),$$

$$R_o \rightarrow R_b \text{ and } A_o \rightarrow A_s.$$

CALCULATIONAL PROCEDURE

The calculational procedure for the temperatures within the fuel material is schematically presented in Figure 2 and is made with the subroutine SINTER listed in the Appendix. The input and output variables for this subroutine are given in this listing and the SPINTER program input is given in Table 1. The appropriate integrated thermal conductivity tables for the unsintered and sintered densities are developed

FIGURE 2. *Calculational Steps for the SINTER Program*

TABLE 1. *SINTER Program input*Input Information

FLEN	Fuel Fin Length, ft
E	Extrapolation Distance, ft
PM	Maximum Pin Heating Rate, kW/ft
DP	Pin Diameter, ft
CT	Cladding Thickness, ft
CMF	Coolant Mass Flow Rate, lb/hr
CP	Coolant Specific Heat, Btu/lb-°F
HF	Film Coefficient, Btu/ft ² -°F-hr
HG	Cap Coefficient, Btu/ft ² -°F-hr
CK	Cladding Conductivity, Btu/ft-°F-hr
TI	Inlet Coolant Temperature, °F
TB	Temperature, °F
DENLO	Fraction Theoretical Density Unsintered
DENHI	Fraction Theoretical Density Sintered
FD	Fuel Pellet Outer Diameter, ft
FID	Fuel Pellet Inner Diameter, ft
SEQUM	Number of Segments

at each axial location case during the calculations for the radial temperature distribution. The calculations are repeated for each axial location as well as for fuel where the temperature distribution is desired. Various schemes for picking the desired radial locations for determining the temperature have been used such as locations based on equal volume or equal radial size increments throughout the fuel region. The version listed in the Appendix is for equal size increments.

After the radial temperature distribution has been calculated, print and punch outputs are supplied to the user by the main program called SINTR. The actual SINTR program has many

versions and is used to evaluate temperature dependent conditions within the fuel material. Only the basic scheme for calculating the distribution of radial temperature in the fuel is described in this report.

Programs considering the densities of additional sintering regions can be developed by using the same principles. Since the calculations for each sintered region are based on the same relationships, the development of any number of sintered boundaries involves only an extension of the logic statements within the program. This procedure has been programmed for the HYBRID computer by using a three-region fuel pellet.

SUMMARY AND CONCLUSIONS

The SINTER program has found many applications for evaluating the temperatures within fuel materials. It takes into account the structural changes occurring during irradiation, and the temperature dependent conductivity of the fuel material. By utilizing the table-look-up procedures for a temperature integral of the conductivity, either tabular values or analytical approximations for this function may be used in the calculational procedure. The general procedure can be adapted for considering various irradiation effects on the thermal conductivity of the fuel materials. The direct hook-up of the SINTER program to other calculational procedures has made it a useful tool in evaluating irradiation behavior of reactor fuel materials. The actual adjustment of the parameters for the sintered density, and temperatures at which sintering occurs, is performed by the HYBRID computer. A version of this program is used to make correlations with the observations made on fuel materials irradiated under prototypical conditions. A three-region version of the SINTER subroutine is used in these correlations.

APPENDIX

RADIAL TEMPERATURE DISTRIBUTION CALCULATIONAL PROGRAM

APPENDIX 1

RADIAL TEMPERATURE DISTRIBUTION CALCULATION PROGRAM

SUBROUTINE SINTER

SINTER SUBROUTINE

A SUBROUTINE TO CALCULATE THE RADIAL TEMPERATURE DISTRIBUTION
IN AN ANNULAR PELLET ASSUMING SINTERING ABOVE TB AND TEMPERATURE
DEPENDENT CONDUCTIVITY*

*** NOMENCLATURE

INPUT

TB = SINTERING TEMPERATURE - (F)
TO = SURFACE TEMPERATURE - (F)
RO = OUTER RADIUS
AO = INITIAL INNER RADIUS
QO = LINEAR HEAT GENERATION - (BTU/(HR*FT))
DU = UNSINTERED FRACTION THEORETICAL DENSITY
DS = SINTERED FRACTION THEORETICAL DENSITY
NR = NUMBER OF REGION (NR+1=NUMBER OF TEMPERATURES)

OUTPUT

TR = TEMPERATURES - (F)
TMAX = MAX TEMPERATURE WITHOUT SINTERING - (F)
RB = RADIUS OF SINTERED REGION
AS = FINAL INNER RADIUS
--ALL LENGTH MEASUREMENTS IN SAME UNITS--

*** SUBROUTINE AND FUNCTIONS ***

YTON = NEWTON APPROXIMATION $Y-B*\text{ALOG}(Y)-C=0$
TABLE = CREATES VALUES IN TABLE OF T
S = CALCULATE INTEGRAL OF THERMAL CONDUCTIVITY-(BTU/(HR*FT))
T = INTERPOLATS FOR TEMPERATURE - (F)

COMMON / SNTR / TB, TO, RO, AO, QO, DU, DS, NR,
1 TR(50), TMAX, RB, AS
DATA PI/3.141592 /

*** INITIAL VALUES ***

10 SO = S(TO,DU)
AR2= (AO/RO)**2
CU = .25*QO / (PI*(1.-AR2))

*** CALCULATE TMAX ***

IF(AR2.GT.1.E-10) GO TO 11
SC = SO + CU
GO TO 12

```

11 CONTINUE
   SC = SO + CU*( 1.-AR2 + AR2*ALOG(AR2) )
12 CONTINUE
   CALL TABLE(DU,TO)
   TMAX = T(SC)

   *** CALCULATE RB ***

   IF(TMAX.LE.TB) RB=-1.
   IF(TMAX.LE.TB) GO TO 20
   SB = S(TB,DU)
   CK = 1.- (SB-SO)/CU
   IF(AR2.GT. 1.E-8) GO TO 15
   RR = RO * SQRT(CK)
   GO TO 20
15 CONTINUE
   RB = RO * SQRT( YTON(AR2,CK) )
20 CONTINUE

C   *** CALCLATE AS ***

   AS = AO
   IF(AO.GT.RB) GO TO 30
   SB = S(TB,DS)
   AS = SQRT( RB**2 - DU*( RB**2 - AO**2 ) / DS )
   AS2 = (AS/RB)**2
   QB = QO * ( 1. - ( 1.- RB**2/RO**2 ) / ( 1.-AR2) )
   CS = .25*QB / ( PI*(1.-AS2) )
   CONTINUE

   *** CALCULATE TEMPERATURE DISTRIBUTION ***

   NCALL = 0
   RR = RO
   DELR = (RO-AS)/FLOAT(NR)
   TR(1) = TO
   DO 40 I=1,NR
   RR = RR - DELR
   IF( RR .GE.RB) GO TO 35
   IF(NCALL.EQ.0) CALL TABLE(DS,TB)
   NCALL = 1
   RC2 = (RR /RB)**2
   SC = SB + CS * ( 1.-RC2 + AS2*ALOG(RC2) )
   TR(I+1) = T(SC)
   GO TO 40
35 CONTINUE
   RC2 = (RR /RO)**2
   IF(RC2.GT.1.E-10) GO TO 36
   SC = SO + CU
   GO TO 37
36 CONTINUE
   SC = SO + CU * ( 1.-RC2 + AR2*ALOG(RC2) )
37 CONTINUE
   TR(I+1) = T(SC)

```

```

40 CONTINUE
   RETURN
   END

```

SUBROUTINES

```

      FUNCTION YTON(B,C)
C
C   MAKES NEWTON APPROXIMATION FOR  $Y-B*\text{ALOG}(Y)-C=0$ 
C
      NCT = 0
      YA = C
10  YTON = ( C - B*(1.-ALOG(YA)) ) / (1.- B/YA )
      TEST = ABS( YTON/YA - 1.)
      YA = YTON
      NCT = NCT + 1
      IF(NCT.GT.100) GO TO 20
      IF( TEST.GT. 1.E-8) GO TO 10
      RETURN
20  WRITE(6,25) TEST
25  FORMAT(43H FAILURE TO CONVERGE IN YTON (YTON/YA)-1 = ,E10.4 )
      RETURN
      END

      FUNCTION S(T,D)
C
C   CALCULATES INTEGRAL (KDT)
C   T = TEMPERATURE -F
C   D = FRACTION OF THEORETICAL DENSITY
C   S = INTEGRAL FUNCTION - BTU/(HR*FT)
C
      SF(X)=X**.613/(.09084-.07306*D) -(54.615*D+167.173)*EXP(-.00154*X)
      IF(T.GT.3272.) GO TO 10
      S= SF(T)
      RFTLIRN
10  IF(T.GT.5432.) GO TO 20
15  S = SF(3272.) + 1.31769*(T-3272.)
      RETURN
20  CONTINUE
      WRITE(6,25)
25  FORMAT(39HMELTING OCCURED - CALCULATIONS IN ERROR )
      GO TO 15
      END

      SUBROUTINE TABLE(D,T)
C
C   SUBROUTINE TO SET UP COEFFICIENTS IN A QUADRATIC TABLE
C   INTERPOLATION. VALUES ARE IN LABELED COMMON
C

```

```

COMMON /TBL / TEM(7), FAC(2,6), SEM(6)
DATA TEM(7), FAC(1,6), FAC(2,6) / 5432., 7.894737, 0.0 /

C
IF(T.GE.3272.) GO TO 100
TEM(1) = T
DT = .2*(3272.-T)
SEM(1) = S(T,D)
DO 10 K=1,5
TEM(K+1) = TEM(K) + DT
SEM(K+1) = S( TEM(K+1), D )
TC = TEM(K) + .5*DT
SC = S( TC, D )
DS = SEM(K+1) - SEM(K)
FAC(2,K) = DT*(SC - .5*( SEM(K)+SEM(K+1) )) / (DS*(SC-SEM(K))
1 *(SEM(K+1)-SC) )
FAC(1,K) = DT/DS - DS*FAC(2,K)
10 CONTINUE
100 RFTURN
END

FUNCTION T(S)
C
C FUNCTION TO FIND TEMPERATURE, (F), BY A QUADRATIC TABLE INVERSION
C TABLE(D,T) MUST BE CALLED FIRST TO CREAT LABLED COMMON
C
COMMON /TBL / TEM(7), FAC(2,6), SEM(6)
C
DO 10 K=1,6
KC = 7-K
IF(S.LT.SEM(K)) GO TO 10
SC = S - SEM(K)
T = TEM(K) + FAC(1,K)*SC + FAC(2,K)*SC**2
GO TO 20
10 CONTINUE
WRITE(6,15) TEM(1)
15 FORMAT(33H0TEMPERATURE LESS THAN REFERENCE, F8.0 )
SC = S - SEM(1)
T = TEM(1) + FAC(1,1)*SC + FAC(2,1)*SC**2
20 RFTURN
END

```

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