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DEVELOPMENT REPORT

**A PROCEDURE FOR CALCULATION OF
STEADY-STATE TEMPERATURE IN
ZIRCALOY-CLAD, BULK-OXIDE
FUEL ELEMENTS USING THE FIGRO
COMPUTER PROGRAM**

(LWBR Development Program)

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IN ZIRCALLOY-CLAD, BULK-OXIDE FUEL ELEMENTS
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(LWBR Development Program)

I. Goldberg

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Procedures are specified for using the FIGRO computer program to calculate clad and fuel temperatures in Zircaloy-clad, bulk-oxide fuel rods. Rod temperature distributions are calculated at specified depletions from input values of (1) surface heat flux, (2) coolant temperature and pressure, (3) heat transfer coefficients, (4) temperature-dependent clad thermal conductivity, (5) temperature-dependent and concentration-dependent gas thermal conductivity in the fuel-clad gap, and (6) temperature-, depletion-, and porosity-dependent fuel thermal conductivity. Provision is made to account for temperature increases due to long-time crud and corrosion film buildup and steam properties are utilized to compute gap conductance in a defected fuel element. Gap dimensions are adjusted to account for differential thermal expansion and fuel swelling. All major assumptions and analytical procedures are identified. Material property inputs are specified on both a best estimate and design (worst-case) basis. These procedures were developed as part of the LWBR development program.

A PROCEDURE FOR CALCULATION OF STEADY-STATE TEMPERATURE
IN ZIRCALOY-CLAD, BULK-OXIDE FUEL ELEMENTS
USING THE FIGRO COMPUTER PROGRAM
(LWBR Development Program)

I. Goldberg

I. INTRODUCTION

Calculation of fuel element internal temperature is basic in fuel element design and evaluation of irradiation tests due to the strong temperature dependence of the mechanical properties of both oxide fuel and Zircaloy cladding. In bulk-oxide fuel elements temperature levels are governed by the thermal properties of oxide fuel, cladding and fuel-clad gap, or interface, as well as the interdependence of fuel thermal properties and fuel volume swelling. Thus, the FIGRO computer program (References 1 and 2) was developed to provide the computational capability to account for the above effects. This report describes procedures that have been developed, using FIGRO, to determine fuel element internal temperatures for both the analysis of irradiation test performance and the evaluation of fuel element designs.

A general description of the computational procedure used in FIGRO and the major input and output variables are presented. Input specifications are presented

for both fueled and plenum regions of the fuel element and thermal and physical property inputs are specified and documented for Zircaloy-cladding, oxide fuel, fuel-clad gap, or interface, and coolant. Where appropriate, brief discussions of the FIGRO calculational techniques are provided. Detailed description of the FIGRO computational model is presented in References 1 and 2.

II. GENERAL DESCRIPTION OF THE PROCEDURE

A. Basic Analytical Approach in the FIGRO Program

The FIGRO program calculates the one-dimensional, steady-state temperature distribution throughout the fuel and clad for axisymmetric, Zircaloy-clad, bulk-oxide fuel rods. Temperature distributions are computed at specified depletions from input values of (1) surface heat flux (or fuel center temperature), (2) coolant temperature and pressure, (3) heat transfer coefficients, (4) temperature-dependent clad thermal conductivity, (5) temperature-dependent and concentration-dependent gas thermal conductivity in the fuel-clad gap, and (6) temperature-, depletion-, and porosity-dependent fuel thermal conductivity.

Differential thermal expansion of the fuel and clad is computed internally from user specification of the appropriate temperature dependent coefficients for each material. Fuel volume swelling of bulk-oxide fuel is computed internally and accommodation of this swelling in internal porosity and pellet radial and axial dimensional changes is accomplished according to user specification. These two effects thus determine the fuel-clad gap thickness at operating conditions.

Heat transfer across the fuel-clad gap, or interface, is computed either from a user specified value of gap conductance or computed internally utilizing a model which accounts for (1) conduction through a gas layer, (2) conduction through solid points of contact, and (3) radiant heat transfer.

B. Major Variables

1. Input

- (a) Dimensions of the element (fuel, clad, etc.)
- (b) Thermal conductivity and thermal expansion coefficients of fuel, clad, plenum spring, etc.
- (c) Initial fuel porosity and compartment depletion.
- (d) Radial dependence of heat generation rate.
- (e) Clad surface heat flux or fuel center temperature.

2. Output

- (a) Temperatures in fuel and clad regions.
- (b) Average pellet heat generation and fissioning rate.

- (c) Total fuel volume swelling.
- (d) Dimensional changes resulting from thermal expansion and fuel volume swelling.

III. FIGRO INPUT PREPARATION

Input to the FIGRO program can be described as belonging to four categories. These are (a) control data, (b) geometry, (c) thermal and physical properties, and (d) forcing functions.

Each input quantity is described by the letter F (corresponding to a floating point number) or the letter X (corresponding to a fixed point number) together with the card number and word number (indicated as a subscript). A definition of the quantity follows and standard values are given for both best estimate and design procedures. Documentation of the standard values are supplied where appropriate. Although the FIGRO program has the capability for computation of temperature in fuel rods containing annular pellets or two radial zones of fuel (or annular pellet with center insert), only the solid cylindrical geometry case will be discussed in detail.

A guide to FIGRO input requirements is provided in Appendix A and a sample problem exhibiting many of the features of input and output is included as Appendix B.

A. Fuel Region

1. Control Data

Control data make provision for the setup of computational technique and the form of output required.

Symbol X_1

Card 1300

Word 1

This quantity determines the number of equal thickness annuli, or rings, in the fuel used for computation of temperature and fuel volume swelling. Any number up to 100 is permissible.

Analytic Procedure

Ten radial sections have been found to provide sufficient accuracy for solid cylindrical geometry. For fuel rods significantly different, comparison calculations should be performed to determine the sensitivity to this parameter.

Standard

$$X_2 = 10$$

$X_2 = 0$, full Output printed

$X_2 = 1$, reduced Output printed

The reduced output includes, in addition to a listing of the input, temperatures at the clad outer and inner radius and at the fuel outer and inner radius, gap conductance, fractional fuel volume swelling, residual porosity, average fuel and clad heat generation and fissioning rates, fuel depletion, and revised fuel pellet dimensions. The full output prints, in addition to a listing of the input and the data contained in the reduced output, fuel thermal conductivity and conductivity integral

$$\int_0^T k dT$$

as a function of temperature from 0 to 7000F, the porosity value used in the thermal conductivity multiplier, and temperature and conductivity integral

$$\int_{T_s}^{T_i} k dT$$

at each radial station (r_i) which define the boundaries of the equal thickness calculational annuli. T_s is the fuel pellet surface temperature.

Analytic Procedure

Ordinarily, the full output (three printed pages per case) provides useful data. However, for parametric studies involving many cases, the reduced output should be adequate.

Standard

$X_2 = 0$

2. Geometry

In the design procedure, the geometry is specified so that the most limiting case is taken. If more than one criterion is considered, the most limiting geometry can be different for each criterion. As-fabricated measurements are normally available for evaluation of test data.

a. Clad

Symbols F_1, F_2

Card 300

Words 1 and 2

F_1 = clad inside radius (inches)

F_2 = clad outside radius (inches)

Analytic Procedure

To maximize temperature rise in the fuel, specify these radii within manufacturing tolerance such that the fuel-clad gap and clad outside radius are maximized. When FIGRO results are to be used as input for analyses of other design criteria (e.g., clad burden, clad thickness requirements, etc.) specify clad dimensions consistent with the most limiting case for the criterion considered.

Symbol F_3

Card 300

Word 3

F_3 = clad axial length (inches)

Analytic Procedure

Normally, the clad length is specified as unity. Note that the clad length must be specified equal to the fuel length since axial heat transfer is not considered.

Standard

$F_3 = 1.0$

b. Fuel

Symbol X_2

Card 100

Word 2

$X_2 = 1$, one radial zone of fuel (solid or annular pellet).

$X_2 = 2$, two radial zones of fuel.

Analytic Procedure

For solid cylindrical geometry, a one-radial fuel zone should be selected. For analyses of irradiation tests involving solid pellets, a one-radial fuel zone is ordinarily represented. However, the description of the fuel as two-radial zones may be useful in a calculation to determine the sensitivity of fuel temperature to circumferential cracking or, in analysis of an irradiated specimen, if, after metallurgical examination, some metallurgical temperature "marker"

(melting, coring, columnar grain growth, etc.) is observed. In that case, the fuel region can be represented as two zones with the interface at the inferred temperature.

Symbols F_1, F_2

Card 1200

Words 1 and 2

F_1 = fuel inside radius (inches).

F_2 = fuel outside radius (inches).

Analytic Procedure

For design, the fuel inside radius is normally specified as zero. To maximize temperature rise, the fuel outside radius should be specified within manufacturing tolerance such that the fuel-clad gap is maximized. When FIGRO results are to be used as input for analyses of other design criteria, specify fuel dimensions consistent with most limiting case for the criterion considered.

Symbol F_3

Card 1200

Word 3

F_3 = fuel axial length (inches).

Analytic Procedure

Normally, the fuel pellet length is specified as unity. Note that the fuel length must be specified equal to the clad length.

Standard

$F_3 = 1.0$

3. Thermal and Physical Properties

a. Clad

(1) Thermal Conductivity

Symbol F_4

Card 300

Word 4

F_4 = number of thermal conductivity-temperature ($k_c - T$) pairs to be supplied on card series 301.

$2.0 \leq F_4 \leq 5.0$.

The clad thermal conductivity is treated in FIGRO as a piecewise linear function of temperature. From two to five thermal conductivity-temperature pairs may be supplied to define the variation with temperature.

Standard

$$F_4 = 5.0$$

Symbols $F_{11}, F_{12} \dots F_{n1}, F_{n2}$

Cards 301, 302, 303, $2 \leq n \leq 5$

This is a card series of from one to three cards which supply clad thermal conductivity-temperature pairs as follows:

$$\left. \begin{array}{l} F_{i1} = \text{clad thermal conductivity (Btu/hr-ft-}^{\circ}\text{F)} \\ F_{i2} = \text{temperature (}^{\circ}\text{F) corresponding to } F_{i1} \end{array} \right\} i = 1, 2, 3, \dots, n$$

The temperature values must be in ascending order and must be non-negative.

Analytic Procedure

Thermal conductivity of irradiated Zircaloy is given as

$$k_c(\text{irradiated}) = [0.95] \left[7.23 + (2.41 \times 10^{-3})T + (1.3 \times 10^{-6})T^2 \right] \quad (1)$$

where T is in degrees F and k_c in Btu/hr-ft- $^{\circ}$ F. The thermal conductivity-temperature pairs should be input so as to cover the temperature range of interest.

Standard

For a range of 600 to 800 degrees F

$$F_{11}, F_{12} = 8.69, 600.0$$

$$F_{21}, F_{22} = 8.88, 650.0$$

$$F_{31}, F_{32} = 9.08, 700.0$$

$$F_{41}, F_{42} = 9.28, 750.0$$

$$F_{51}, F_{52} = 9.49, 800.0$$

(2) Thermal Expansion

Symbols F_1, F_2, F_3

Card 600

Words 1, 2, and 3

These three values determine the clad linear thermal expansion from the following relationship.

$$\int_{T_r}^T \alpha_c(T) dT = F_1 + F_2 T + F_3 T^2; T = \text{degrees C} \quad (2)$$

where

α_c = linear coefficient of thermal expansion, function of temperature

T_r = 20 degrees C = 68 degrees F.

If the 600 card is omitted, the F_i are set to zero.

Clad thermal expansion is used in the program to determine the fuel-clad gap at operating temperature. Equation (2) is evaluated at the converged clad average temperature and the residual gap thickness at operating temperature is determined by vector addition of the increase in clad inner radius to the increase in fuel outer radius due to thermal expansion and fuel volume swelling.

Standard

Based on Reference 3 data, for Zircaloy, assuming isotropic thermal expansion;

$$\begin{aligned} F_1 &= 6.0 \times 10^{-5} \\ F_2 &= 5.14 \times 10^{-6} \\ F_3 &= 3.80 \times 10^{-9} \end{aligned}$$

b. Fuel

(1) Fuel Volume Swelling

Symbol X_3

Card 100

Word 3

$X_3 = 0$, a modified version of the Greenwood-Speight model (Reference 4) is used to describe fuel volume swelling due to gaseous fission products and a linear model with depletion ($K \cdot D$) is used to describe fuel volume swelling due to solid fission products.

$X_3 = 1$, overall swelling model described as $K \cdot (DT)^{3/2}$,
 D = depletion and T = temperature.

The calculation of fuel volume swelling can be performed either by a model developed from the approach of Greenwood and Speight, modified by utilization of van der Waal's gas law in place of the perfect gas law and adding the effect of an externally applied pressure to that applied to the gas bubble by surface tension action, or by a model developed from an assumption of fixed bubble number and spacing. (See Reference 1 for derivation of both models). In both models fuel swelling is assumed to be a state-point function of the conditions of

temperature and depletion existing at the time of the calculation. The fuel swelling equations are explicitly solved for each calculational ring and averaged over the total volume.

Analytic Procedure

The Greenwood-Speight swelling model in conjunction with a linear model for solid fission product volume swelling is specified for both best estimate and design procedures since this model was utilized in the experimental verification (Reference 5) of the CYGRO-1 program (Reference 6) and is used in the procedure for analysis of fuel rod performance (Reference 7).

Standard

$X_3 = 0$ for design and best estimate.

Symbol X_4	Card 100	Word 4
$X_4 = 0$, coefficient of fuel volume swelling due to solid fission products (K) = 0.0035 per 10^{20} f/cc.*		
$X_4 = 1$, coefficient K to be input on card 400.		

Solid fission product volume swelling is described as linear with depletion ($K \cdot D$). Reference 8 describes an analysis in which K is calculated to be 0.35 percent per 10^{20} f/cc. However, this analysis assumes each fission product nucleus is present in an uncombined state. Thus a value of 0.35 percent per 10^{20} f/cc should be an upper limit.

Analytic Procedure

Fuel volume swelling affects calculation of temperature in the following two ways:

1. Temperature rise tends to be increased by increased radial heat path and declining thermal conductivity due to increased fuel porosity (increased fuel porosity results in declining thermal conductivity).
2. Temperature rise tends to be decreased by reduction of fuel-clad gap thickness.

*f/cc represents fissions per cubic centimeter.

Since these two effects tend to be compensating and since a value of 0.25 percent per 10^{20} f/cc is utilized in Reference 7 procedure, a value of $K = 0.0025$ per 10^{20} f/cc is specified for both best estimate and design purposes.

Standard

$$X_4 = 1$$

Symbol F_1

Card 400

Word 1

F_1 = coefficient of fuel volume swelling due to solid fission products.

Analytic Procedure

Follow the procedure for the preceding Symbol X_4 on Card 100.

Standard

$$F_1 = 0.0025$$

Symbol 5

Card 200

Word 5

$F_5 = p_H$ (internal hydrostatic pressure, psia) used in the modified Greenwood-Speight fuel swelling model.

The modified version of the Greenwood-Speight fuel swelling model used in FIGRO describes fuel volume swelling as a function of temperature, depletion, fission rate, and externally applied pressure. The value of this last parameter is user supplied.

Analytic Procedure

The value assigned to externally applied pressure to the fuel is clearly a function of geometry, temperature, depletion, and clad diameter shrinkage. In a calculation involving a fuel rod with relatively large fuel-clad gap performed for early in life conditions, p_H would be essentially zero since fuel-clad contact would not be expected to have occurred. Conversely, p_H would be expected to be relatively large for late in life conditions of a fuel rod at an initially small clearance gap. These effects can be evaluated independently by use of a program such as CYGRO. It is suggested, therefore, that the user individually determine this parameter for the specific conditions involved: that is, by CYGRO-FIGRO iteration. For survey calculations, a value equal to that of the coolant pressure is suggested as an approximate average over lifetime.

$X_5 = 0 = T_{gr}$ (fission gas release temperature, degrees F)
not used.

$$X_5 = 1 \begin{cases} T_{gr} = 2930 + 22.667D + 0.32667D^2; \\ 0 < D < 30 \\ T_{gr} = 2544; D \geq 30 \end{cases} \quad (3)$$

$$X_5 = 2 \begin{cases} T_{gr} = B_1 + B_2D + B_3D^2 & 0 < D < D_{sw} \\ T_{gr} = B_1 + B_2D_{sw} + B_3D_{sw}^2 & D \geq D_{sw} \end{cases}, \quad (4)$$

where D and D_{sw} have the units of 10^{20} f/cc of 100 percent dense fuel.

This option provides for the reduction of fuel volume swelling by release of fission gases from the fuel matrix. This is handled in FIGRO by assuming that all of the fission gases are released from the matrix above a user specified temperature, which may be a function of depletion. Thus, for all calculational rings above the gas release temperature, only the volume swelling due to solid fission products contributes to the total pellet volume swelling.

Analytic Procedure

The reduction of fuel volume swelling due to release of fission gases from the matrix should be accounted for in both best estimate and design procedures. It is suggested that the user generate coefficients for the determination of gas release temperature based on the specific conditions. This is discussed more fully below.

Standard

$X_5 = 2$ for design and best estimate.

$F_1, F_2, F_3 = B_1, B_2, B_3$ in Equation (4)

$F_4 = D_{sw}$ in Equation (4).

Analytic Procedure

Reference 9 proposes a model for fission-gas release by bubble migration along the thermal gradient. In this model, similar to that proposed for fabricated pore migration (coring), fission gas bubble migration is a function of

bubble diameter, temperature, and time. An analytical procedure utilizing this model has recently been developed and correlated with experimental measurements of fuel rod gas release. This procedure is described in Section III.A.3.c, which deals with the effect of fission gas release on fuel - clad gap conductance. Work is in progress to utilize this model in predictions of reduction of fuel swelling at a specific axial location (one pellet).

A conservative interim method to account for gas release by this mechanism is to calculate a temperature that results in significant bubble migration in a time much less than the lifetime of the element. A time of 1000 hours was selected. The Reference 9 model predicts a gas release temperature of 4100F for ThO₂-based fuels, 3900F for ZrO₂-based fuels, and 3300F for UO₂ for 1000 hours.

Standard

$$\begin{aligned} F_1 &= 4100.0 \text{ for ThO}_2\text{-based fuels} \\ &3900.0 \text{ for ZrO}_2\text{-based fuels} \\ &3300.0 \text{ for UO}_2\text{-based fuels} \\ F_2 &= 0.0 \\ F_3 &= 0.0 \\ F_4 &= \text{Any value} > 0.0. \end{aligned}$$

(2) Thermal Conductivity. Fuel thermal conductivity is computed in FIGRO with the use of the general relationship proposed for bulk-oxide fuels in Reference 10. The general form of the equation used in FIGRO is

$$k = \frac{1-p}{1+\beta p} k_o = k' k_o, \quad (5)$$

where k_o is the conductivity of 100-percent dense fuel, p is the fractional porosity and the multiplier, k' , is a porosity correction factor. The form of k_o used in FIGRO is

$$k_o = \left[\frac{F_1 + F_2 D}{T} + F_3 + F_4 D + (F_5 + F_6 D) T \right]^{-1} \quad T < F_7 \quad (6a)$$

$$k_o = \left[\frac{F_8 + F_9 D}{T} + F_{10} + F_{11} D + (F_{12} + F_{13} D) T \right]^{-1} \quad T \geq F_7 \quad (6b)$$

where k is in watts/cm-°C, T is temperature in degrees K, D is depletion in 10^{20} f/cc of 100-percent dense fuel, and F_1 to F_{13} are user supplied constants.

Either 6 or 13 numbers may be supplied. If 6 are supplied, Equation (6a) is used to compute k_o for all temperatures. If 13 are supplied, F_7 is the temperature (degrees K) below which Equation (6a) is used and above which Equation (6b) is used to compute k_o .

Symbol X_1

Card 1100

Word 1

$X_1 = 1$, porosity correction factor (k' in Equation 5) is set equal to 1.0.

$X_2 = 2$, k' computed as in Equation (5), β set equal to 0.5.

$X_3 = 3$, k' computed as in Equation (5), β to be input on card 1150.

Standard

$X_1 = 3$

Symbol F_1

Card 1150

Word 1

$F_1 = \beta$ in Equation (5).

Analytic Procedure

The constant β in the porosity correction factor is a quantity which, according to Reference 10, is primarily a function of pore shape and orientation. Suggested values of β for high and low density fuel are presented in Reference 10 and these values should be used in best estimate evaluations. For design purposes the assumptions are made that the first three volume percent of porosity is spherical and the value of β , if it alone were present, would be 0.5, and that porosity in excess of three volume percent is of such a nature that the value of β , if it alone were present, would be 3.0. Thus, when two types of porosity are present the resulting value can be calculated by assuming, first, that only one type is present, and second that the resulting thermal conductivity is that of a matrix through which the other type is distributed. The resulting calculated values of β as a function of density are presented below. Since the thermal conductivity values for 100-percent dense $\text{ThO}_2\text{-UO}_2^*$ were obtained utilizing these values of β , the overall model is self consistent.

For low density fuels manufactured by the sugar-additive process a value of $\beta = 2.0$ is suggested for design purposes.

*The thermal conductivity values for 100-percent dense $\text{ThO}_2\text{-UO}_2$ compositions were determined from data obtained at Battelle Memorial Institute in a study of fabrication, characterization, and thermal property measurements of $\text{ThO}_2\text{-UO}_2$ fuel materials.

Standard

	<u>% T.D.</u>	<u>F₁</u>
	100	0.5
	99	0.5
Design: High Density Fuel;	98	0.5
	97	0.5
	96	1.16
	95	1.55
	94	1.82
	93	2.01
	92	2.15
	91	2.26
Low Density; F ₁ = 2.0		
Best Estimate: High Density; F ₁ = 0.5 Low Density F ₁ = 0.7		

Symbols F₁ to F₁₃

Cards 1101 to 1103

Words 1 to 13

These cards contain the data for computation of k_o in Equation (6).

Analytic Procedure

Reference 10 recommends values of constants in Equation (6) for UO_2 , ZrO_2-UO_2 , and ThO_2-UO_2 compositions. However, more recent data on ThO_2-UO_2 compositions have become available through studies made at Battelle Memorial Institute.

As shown in Figure 6 of Reference 10, the thermal conductivity of ThO_2-UO_2 is sensitive to composition in the range of zero to 30 weight percent UO_2 . The thermal conductivity of ZrO_2-UO_2 , however, is relatively insensitive to composition in the range of 20 to 90 weight percent UO_2 as shown in Figure 7 of Reference 10. Thus, constants for Equation (6) will be specified as a function of composition for ThO_2-UO_2 but only one set of constants will be specified for ZrO_2-UO_2 compositions. The ThO_2-UO_2 standard constants do not reduce to the UO_2 constants at a ThO_2 mole fraction of zero, presumably due to differences in experimental technique. However, the difference is small (approximately 4 percent).

For design purposes, the following engineering factors, to account for uncertainties and scatter of data, are suggested.

- (a) An engineering factor of 0.9 to the best estimate integrated thermal conductivity for fuel 97 percent of theoretical density (T.D.) or greater.
- (b) An engineering factor of 0.95 to the best estimate integrated thermal conductivity for fuel less than 97 percent T.D.

Standard

Fuel	F_1	F_2	F_3	F_4	F_5	F_6
$UO_2 \geq 97\% \text{ T.D.}$	2000.0	684.4	7.4519	0.0	0.02174	0.0
$UO_2 < 97\% \text{ T.D.}$	1894.7	648.4	7.0597	0.0	0.02059	0.0
$ThO_2-UO_2 \geq 97\% \text{ T.D.}$	2000.0	684.4	*	0.0	+	0.0
$ThO_2-UO_2 < 97\% \text{ T.D.}$	1894.7	648.4	*	0.0	+	0.0

$$*F_3 = A[2.6786m_1 - 0.83519m_2 + 40.4117m_1m_2] \quad (7)$$

$$+F_5 = A[0.02248m_1 + 0.0198m_2] \quad (8)$$

where m_1 = mole fraction of UO_2 ; m_2 = mole fraction of ThO_2 , and $A = \frac{1}{0.9}$ for fuel ≥ 97 percent T.D. and $\frac{1}{0.95}$ for fuel < 97 percent T.D.

For ZrO_2-UO_2 , parameters F_1 to F_{13} are used.

	F_1	F_2	F_3	F_4	F_5	F_6	F_7
$ZrO_2-UO_2 \geq 97\% \text{ T.D.}$	2000.0	684.4	50.5574	0.0	0.0	0.0	1922
$ZrO_2-UO_2 < 97\% \text{ T.D.}$	1894.7	648.4	47.8965	0.0	0.0	0.0	1922
	F_8	F_9	F_{10}	F_{11}	F_{12}	F_{13}	
$ZrO_2-UO_2 \geq 97\% \text{ T.D.}$	2000.0	684.4	7.4519	0.0	0.02174	0.0	
$ZrO_2-UO_2 < 97\% \text{ T.D.}$	1894.7	648.4	7.0597	0.0	0.02059	0.0	

(3) Thermal Expansion. Thermal expansion of the fuel is described by the following functional relationship.

$$\int_{T_r}^T \alpha_f(T) dt = F_1 + F_2 T + F_3 T^2, \quad (9)$$

where

α_f = linear coefficient of thermal expansion

T = temperature, degrees C

T_r = 20 C = 68 F.

Fuel thermal expansion is used in the program to determine the fuel - clad gap thickness at operating conditions. Equation (9) is evaluated at the converged fuel average temperature and the increase in fuel outer radius thus determined. Residual gap thickness is determined by vector addition of the increase in fuel outer radius by thermal expansion and by fuel swelling to the increase in clad inner radius due to clad thermal expansion.

Values of F_1 , F_2 , and F_3 in Equation (9) may be user specified. However, values for ThO_2 and $\text{ThO}_2 + 50$ w/o UO_2 are available in the program as an option.

Symbol X_1

Card 1600

Word 1

$X_1 = 1$, user supplies F_1, F_2 , and F_3 of Equation (9) on
Card 1610

$X_1 = 2$, ThO_2 coefficients are used (Reference 11)

$X_1 = 3$, $\text{ThO}_2 + 50$ w/o UO_2 coefficients are used (Reference 11)

If options 2 or 3 are selected, Card 1610 should be omitted.

Analytic Procedure

For ThO_2 , constants for temperatures up to 1832F are given in Reference 11 and can be verified by data in Reference 12 up to a temperature of 4500F. Measurements of thermal expansivity for $\text{ThO}_2 + 10$ w/o UO_2 and $\text{ThO}_2 + 20.4$ w/o UO_2 were performed at BMI (See footnote on page 13). Thermal expansion measurements for UO_2 and $\text{ThO}_2 + 50$ w/o UO_2 are reported in Reference 11. Data on thermal expansion of ZrO_2 - UO_2 compositions are reported in Reference 13.

Standard

$X_1 = 2$, for ThO_2

$X_1 = 3$, for $\text{ThO}_2 + 50$ w/o UO_2

$X_1 = 1$, for intermediate compositions and alternate oxide
fuels.

Symbols F_1, F_2, F_3

Card 1610

Words 1, 2, and 3

These are the three coefficients in Equation (9). They should be supplied when $X_1 = 1$ on Card 1600.

Standard

ThO₂-UO₂ Compositions

<u>Composition</u>	<u>F₁</u>	<u>F₂</u>	<u>F₃</u>
ThO ₂	-1.63 x 10 ⁻⁴	8.17 x 10 ⁻⁶	1.12 x 10 ⁻⁹
ThO ₂ + 10 w/o UO ₂	-2.23 x 10 ⁻⁴	9.42 x 10 ⁻⁶	0.706 x 10 ⁻⁹
ThO ₂ + 20.4 w/o UO ₂	-2.26 x 10 ⁻⁴	8.82 x 10 ⁻⁶	1.24 x 10 ⁻⁹
ThO ₂ + 50 w/o UO ₂	-1.76 x 10 ⁻⁴	8.82 x 10 ⁻⁶	1.33 x 10 ⁻⁹
UO ₂	-1.66 x 10 ⁻⁴	8.25 x 10 ⁻⁶	2.21 x 10 ⁻⁹

In the absence of data, linear interpolation is suggested for intermediate compositions.

ZrO₂-UO₂ Compositions

<u>Composition</u>	<u>F₁</u>	<u>F₂</u>	<u>F₃</u>
ZrO ₂ + 20 w/o UO ₂	-0.732 x 10 ⁻⁴	10.41 x 10 ⁻⁶	0.500 x 10 ⁻⁹
ZrO ₂ + 32 w/o UO ₂	-3.33 x 10 ⁻⁴	11.05 x 10 ⁻⁶	0.340 x 10 ⁻⁹
ZrO ₂ + 50 w/o UO ₂	0.89 x 10 ⁻⁴	8.96 x 10 ⁻⁶	1.53 x 10 ⁻⁹
ZrO ₂ + 94 w/o UO ₂	-6.44 x 10 ⁻⁴	10.97 x 10 ⁻⁶	1.00 x 10 ⁻⁹
UO ₂	-1.66 x 10 ⁻⁴	8.25 x 10 ⁻⁵	2.21 x 10 ⁻⁹

In the absence of data, linear interpolation is suggested for intermediate compositions.

c. Fuel - Clad Gap Conductance. The fuel - clad gap, or interface, heat transfer coefficient is calculated internally utilizing the Ross and Stoute model (Reference 14) modified to include conduction through a physical gap. Fuel growth and differential thermal expansion of the fuel and cladding are used to determine the gap thickness at operating temperature and specified depletion. In addition, heat transfer by radiation across the fuel - clad gap is included. A brief description of the model follows to identify the parameters available to the user. A full description of the model is given in Reference 2.

The temperature rise across the fuel - clad gap or interface is calculated as follows:

$$T_f = T_c + \frac{\phi_f + \phi_c}{2h_g} , \quad (10)$$

where

T_f and T_c = temperatures (degrees F) at the fuel OD and clad ID respectively

ϕ_f and ϕ_c = surface heat fluxes at the fuel OD and clad ID, respectively (Btu/hr-ft²)

h_g = gap, or interface, heat transfer coefficient (Btu/hr-ft²-°F).

The determination of T_c , ϕ_f and ϕ_c are described in Reference 1.

In the present option, h_g is computed from the following relationship.

$$h_g = h_s + h_f + h_r , \quad (11)$$

where

h_s = conduction coefficient through solid points of contact (Btu/hr-ft²-°F)

h_f = conduction coefficient through gas layer at interface (Btu/hr-ft²-°F)

h_r = radiant heat transfer coefficient (Btu/hr-ft²-°F).

Natural convection was not included since it is negligible for physical gap sizes of interest to fuel element design.

Conduction through the solid points of contacting surfaces is given by Ross and Stoute as

$$h_s = \frac{k_m P}{a_o R^{1/2} H} , \quad (12)$$

where

k_m = harmonic mean of the thermal conductivities, k_1 and k_2 , of the contacting surfaces. That is,

$$k_m = \frac{2 k_1 k_2}{k_1 + k_2} \text{ (Btu/hr-ft-°F)}$$

where

P = contact pressure, psi

a_o = empirical constant which determines the mean radius of contact spots = 0.0905 ft^{1/2}

$$R = \text{root mean square of surface roughnesses} = \left[\frac{(R_1^2 + R_2^2)}{2} \right]^{1/2}$$

R_1, R_2 = arithmetic mean roughness heights, feet

H = Meyer hardness of softer solid in contact, psi.

Conduction through the gas layer at the interface is based upon a modification to Ross and Stoute such that conduction through a physical gap at the interface is included, that is,

$$h_f = \frac{k_f}{C[R_1 + R_2] + [g_1 + g_2] + t}, \quad (13)$$

where

R_1, R_2 = arithmetic mean roughness heights, feet

C = dimensionless contact coefficient related to the contact pressures

$g_1 + g_2$ = "temperature jump distances" for the gas at the interface, feet

t = physical thickness of gas gap separating the two surfaces, feet.

The terms $C[R_1 + R_2]$ and $[g_1 + g_2]$ can be considered as effective gap thicknesses which, when combined with the physical separation t , determine a total effective resistance to heat transfer by conduction through the gas layer at the interface.

While radiant heat transfer at the fuel-clad interface is usually negligible for typical operation, the radiant contribution has been programmed to account for extreme cases where the radiation contribution becomes significant. An effective radiation coefficient of heat transfer is computed from

$$h_r = \frac{\mathcal{A}_{1,2} \sigma [T_f^4 - T_c^4]}{T_f - T_c} \quad (14)$$

where

$$\begin{aligned} \mathcal{A}_{1,2} &= \frac{1}{\frac{1}{F_{1,2}} + \left(\frac{1}{\epsilon_f} - 1\right) + \frac{A_f}{A_c} \left(\frac{1}{\epsilon_c} - 1\right)} \\ &\cong \frac{1}{\frac{1}{\epsilon_f} + \frac{1}{\epsilon_c} - 1} \quad \text{since } F_{1,2} \cong 1.0 \quad \text{and } A_f \cong A_c \end{aligned}$$

h_r = effective radiation coefficient of heat transfer, Btu/hr-ft²-°F

σ = Stefan-Boltzmann constant = 0.173×10^{-8} Btu/hr-ft²-(°R)⁴

T_f = temperature of fuel surface, degrees Rankine (°R)

T_c = temperature of clad surface, degrees Rankine (°R)

$F_{1,2}$ = geometrical factor = 1.0 for infinite parallel planes

A_f = area of fuel surface

A_c = area of clad surface

Symbols F_1, F_2

Card 700

Words 1 and 2

$F_1 = \epsilon_c$, clad surface emissivity

$F_2 = \epsilon_f$, fuel surface emissivity.

Analytic Procedure

At typical gap sizes and heat fluxes, radiant heat transfer at the fuel-clad gap is small compared to conduction. For calculations involving large gaps and/or high heat fluxes, values of emissivity for clad and fuel are obtainable from Reference 15 and from References 8, 16, and 17, respectively.

Standard

Design; $F_1 = 0.3$, $F_2 = 0.35$

Best Estimate: Check references for materials at temperatures of interest.

Symbols F_1, F_2

Card 1000

Words 1 and 2

F_1 = "temperature jump distance" of initial filling gas (g_i^r) in micro-inches at $P_r = 14.7$ psia and $T_r = 68F$

T_2 = "temperature jump distance" of fission gases (g_{fg}^r) in micro-inches at $P_r = 14.7$ psia and $T_r = 68F$.

The "temperature jump distances," $g_1 + g_2$ in Equation (13) account for the fractional exchange of energy of individual gas molecules with the solid surfaces and are most significant for small effective gaps where the mean free path of the gas is significant compared to the gap thickness. "Temperature jump distance" values were computed by Ross and Stoute from heat transfer data on contacting UO_2 and Zr surfaces and may be assumed to be proportional to the mean free path of the gas and, hence, directly proportional to temperature and inversely proportional to pressure.

Since "temperature jump distance" values were obtained specifically for helium, argon, and for fission gases, but not for mixtures of these gases, it is assumed that the "temperature jump distance" is a linear function of thermal conductivity of the mixture such that

$$g = g_1 + g_2 = \frac{1}{k_{fg} - k_i} (g_{fg} - g_i)k_g + (k_{fg}g_i - k_i g_{fg}) \quad , \quad (15)$$

where the subscripts f, g, and i refer to fission gas and initial filling gas, respectively, and k_g is the thermal conductivity of the mixture.

A correction for the effect of temperature and for the variation in pressure caused by gap closure and release of fission gases is given by

$$g = g_r \left(\frac{P_r}{P_2} \right) \left(\frac{T_2}{T_r} \right), \quad (16)$$

where

T_2 = average temperature of gap, degrees R

g_r = "temperature jump distance" at reference temperature $T_r = 68.7^\circ\text{F}$ and pressure $P_r = 14.7$ psia

$$P_2 = \frac{\frac{n}{v} RT_2}{N_a} \text{ (psia)}$$

$\frac{n}{v}$ = total number of gas atoms/gap + plenum volume

R = universal gas constant = 0.0236 (psia ft³/gm mole - °R)

N_a = Avogadro's number = 6.02×10^{23} atoms/gm mole.

Analytic Procedure

The "temperature jump distance" values for helium and fission gases are given in Reference 14. In the case of a defected element in a water environment it is assumed that supersaturated steam at system pressure is present in the gap. Thus, the "temperature jump distance" is negligibly small.

Standard

$$\left. \begin{aligned} F_1 \text{ (helium)} &= 244.0 \text{ (Reference 14)} \\ F_2 \text{ (fission gases)} &= 21.8 \text{ (Reference 14)} \end{aligned} \right\} \text{ Non-defected elements}$$

$$F_1 \text{ (steam)} = 0.0, \text{ defected elements}$$

Symbols F_3, F_4, F_7

Card 1000

Words 3, 4 and 7

$F_3 = R_1$, clad surface roughness, micro-inches

$F_4 = R_2$, fuel surface roughness, micro-inches

$F_7 = C$, contact coefficient, dimensionless.

The term $C[R_1 + R_2]$ in Equation (13) represents the effective gap thickness caused by the surface roughness where the coefficient C accounts for surface waviness and error of form and was determined by Ross and Stoute to be a function of contact pressure such that

$$C = 2.75 - 0.000176P_c; \quad P_c \text{ in psia} \quad . \quad (17)$$

This relationship is used in FIGRO. A user option permits the specification of a value of C to be utilized only when a physical gap exists.

Analytic Procedure

For irradiation test specimens, measurements of clad and fuel surface roughness are often available. For design, to maximize temperature, the largest value of clad and fuel surface roughnesses allowable in the manufacturing specifications are used.

For radial gaps greater than 0.5 mils at operating conditions, it is recommended that a smaller value of the constant C (e.g., unity) be employed rather than that reported by Ross and Stoute for contacting surfaces since the effective gap thickness caused by surface waviness and error of form for contacting surfaces may not be as completely effective for separated surfaces.

Standard

Design: F_3 = largest value allowable in manufacturing specifications

F_4 = largest value allowable in manufacturing specifications

$F_7 = 1.0.$

Symbols F_5, F_6

Card 1000

Words 5 and 6

$F_5 = P_c$ (psia), fuel-clad contact pressure (see Equation 17)

$F_6 = H$ (psi), Meyer hardness of softer solid in contact (see Equation 12).

Note: F_5 and F_6 must be specified although fuel and clad may not be expected to come in contact in a specific calculation. If no contact is computed by the program, F_5 and F_6 are not used.

Analytic Procedure

The value assigned to fuel-clad contact pressure is a function of geometry, temperature, and depletion. (See discussion for parameter F_5 on Card 200 in Section III.A.3.b). The user should determine the approximate value for the

specific conditions involved. A value equal to the coolant pressure is suggested for survey studies as representing an approximate average over lifetime.

Since ceramic fuel is presumed to be softer than Zircaloy cladding, a Meyer hardness value appropriate to fuel is suggested as input.

Standard

F_5 = coolant pressure (or user determined)

$F_5 = 1.2 \times 10^5$ (Reference 14).

Symbols $F_1, \dots, F_9$

Cards 800-801

Words 1 to 9

The thermal conductivity of the gas contained at the fuel - clad interface is a function of (1) the relative concentrations of initial filling gas, volatiles released from the fuel, fission gases, and helium produced as a result of a ternary fission mechanism, and (2) the fuel - clad interfacial temperature.

Upgrading of the procedure to account for such additional effects on gap conductance as release of volatile gases from the fuel and ternary fission helium products is under study.

The following functional relationship (see Reference 2 for derivation) is employed in FIGRO for gas thermal conductivity.

$$\log_{10} k_g = a_1 x + [b_1 + c_1 x] \log_{10} T_g + d_1; \quad 0 < x < x_1 \quad (18a)$$

$$\log_{10} k_g = a_2 x + [b_2 + c_2 x] \log_{10} T_g + d_2; \quad x_1 \leq x \leq 1.0 \quad (18b)$$

where

k_g = thermal conductivity of gas contained in gap (Btu/hr-ft-°F)

x = mole fraction of initial filling gas (atoms of initial filling gas / total gas atoms)

T_g = average gap temperature (degrees K).

The gas thermal conductivity is computed internally from user specified values of the coefficients in Equations (18a and 18b). These coefficients are related to the parameters on Cards 800-801 as follows:

$$\begin{array}{ll} F_1 = a_1 & F_6 = a_2 \\ F_2 = b_1 & F_7 = b_2 \\ F_3 = c_1 & F_8 = c_2 \\ F_4 = d_1 & F_9 = d_2 \\ F_5 = x_1 & \end{array}$$

As a user option, values of F_1 to F_9 are built into the program for the case of an initial filling gas of helium. These constants are based on a fit to the data of Ubisch, Hall, and Srivastav (Reference 18) for mixtures of helium, krypton, and xenon where the composition of 15.3 percent krypton and 84.7 percent xenon was used to simulate fission gases. The pertinent constants are:

$$\begin{array}{ll} a_1 = 2.636 & a_2 = 1.468 \\ b_1 = 0.856 & b_2 = 0.825 \\ c_1 = -0.265 & c_2 = -0.104 \\ d_1 = -4.573 & d_2 = -4.308 \\ x_1 = 0.248 & \end{array}$$

This option is utilized if Cards 800 and 801 are omitted.

An additional option has been provided to describe defected elements in a water environment containing steam in the fuel-clad gap where it is assumed that the fission gases are released to the external coolant. The HOH subroutine (Reference 19) is called by this option to describe the unique variation of steam thermal conductivity with temperature. This option is utilized if a value of 1.0 is specified for F_1 on Card 800 and F_2 to F_9 are omitted.

Analytic Procedure

For initial fill gas of helium at one atmosphere utilization of the built-in constants for mixtures of helium and fission gases is suggested as best estimate values. For design purposes, a 10-percent reduction from best estimate values is recommended to account for release of volatiles from the fuel and uncertainties in the design model. This reduction is accomplished by utilization of fictitious values for parameters F_4 and F_9 . For other filling gases (e.g., argon, air) data are available in Reference 21 and elsewhere to enable the user to generate the appropriate constants.

Standard

Non-defected elements; initial fill gas of helium at one atmosphere

Best Estimate: Omit Card 800.

$$\begin{array}{ll} \text{Design: } F_1 = 2.636 & F_6 = 1.468 \\ F_2 = 0.856 & F_7 = 0.825 \\ F_3 = -0.265 & F_8 = -0.104 \\ F_4 = -4.6188 & F_9 = -4.3538 \\ F_5 = 0.248 & \end{array}$$

Non-defected elements; other initial fill gases

Defected elements: $F_1 = 1.0$, F_2 to F_9 omitted.

User determined by fitting data to Equations (18a and 18b).

Symbols F_1, F_2, F_3

Card 1700

Words 1, 2, and 3

$F_1 = \alpha_{fg}$, the number of fission gas atoms produced per fission

$F_2 = r$, ratio of gap volume to gap + plenum volume (initial assembly dimensions)

$F_3 = B$, fraction of fission gas atoms released from fuel material to the gap and/or plenum.

In the present version of FIGRO, the composition of the gas at the fuel-clad interface is based upon an initial one-atmosphere of a filling gas and subsequent dilution by fission gases. The amount of fission gases produced is directly related to fissioning of the fuel. That is,

$$n_{fg} = \alpha_{fg} F, \quad (19)$$

where

n_{fg} = atoms fission gas per cubic centimeter of fuel

α_{fg} = atoms fission gas produced per fission

F = depletion, fissions per cubic centimeter of fuel.

The number of atoms of filling gas per atom of fission gas is given by

$$Z = \frac{\frac{N_a}{V_r} \left(\frac{A_{gap}}{A_{fuel}} \right)}{B \alpha_{fg} F}, \quad (20)$$

where

Z = atoms filling gas per atoms fission gas

N_a = Avogadro's number = 6.02×10^{23} atoms per gram-mole

V_r = volume of gram-mole of gas at standard conditions = 2.25×10^4 cc

A_{gap}/A_{fuel} = ratio of cross-sectional area of "cold" gap to cross-sectional area of fuel. The "cold" gap area is computed from the initial assembly dimensions.

r = ratio of "cold" gap volume to the "cold" gap plus plenum volume

B = fraction of fission gases which are released to the gap.

The composition, x , used in Equations (18a and 18b) is determined from

$$x = \frac{Z}{1 + Z} \quad (21)$$

Note: The value of B , fraction of fission gases released to the gap, is used solely to compute the number of fission gas atoms released to the gap and plenum, and is independent of the gas release correction to the fuel swelling calculation prescribed by word X_5 on Card 100.

Analytic Procedure

Fission of U^{235} yields an estimated 0.3 gas atoms per fission (Reference 9) and this value is suggested for U^{235} fuel. Fission of U^{233} yields an estimated 10 percent greater number of gas atoms than U^{235} . Thus, a value of 0.33 gas atoms per fission is utilized for U^{233} fuel.

Since the thermal conductivity of fission gases is significantly lower than that of helium, the larger the relative concentration of fission gases, the larger the temperature rise across the gap. Thus, the presence of a plenum to collect fission gases will tend to soften the deterioration of gap conductance with increased depletion. The smaller the ratio of gap volume to plenum volume, the larger the softening effect. An overly conservative way to estimate this quantity is to assume that the maximum fuel - clad gap permitted within manufacturing tolerances exists over the entire length of rod combined with the smallest permissible plenum volume. A reasonably conservative estimate that is suggested for design is to assume a nominal fuel - clad gap over the rod length combined with the smallest permissible plenum volume. For irradiation tests, as-fabricated measurements should be used when available.

A model of fission gas release based on bubble migration along the thermal gradient has been formulated in Reference 9. An analytic technique based on this model has been developed and reasonable agreement with experiment has been obtained. This analytic technique predicts fission gas release as a function of time at temperature plus a temperature independent component of 1 percent per 100 days on both a maximum and best estimate bases. Figures 1 and 2 show maximum and best estimate gas release as a function of time and fuel center temperature for ThO_2 -based fuels. To use this technique in design, it is necessary to account for the time-temperature history at every axial location on the rod since the concentration of fission gas in the gap is presumed to depend on the gas release characteristics of the entire fuel stack and to account for the feedback effect of gas release on center temperature.

Figure 1. Maximum Fission Gas Release of ThO_2 Fuel

Figure 2. Best Estimate Fission Gas Release of ThO_2 Fuel

Work is now in progress to program this iterative technique.

A conservative interim method of accounting for gas release for design purposes is to assume that the temperature history of the rod is constant with the peak location at the highest permissible center temperature consistent with some limiting criterion (e.g., melting, central void formation). Using a normalized axial power shape, an axial temperature profile can be constructed and, conservatively assuming that this shape remains constant over life, gas release

as a function of time can be calculated. The calculation can be performed on both a best estimate and maximum release basis for two assumptions; one, that local hot spot peaking factors exist over the entire fuel stack, and the other based on the factors used in thermal design (hot rod factors) with the peak location at the hot spot factors. It is recommended for design, that the combination of maximum gas release and hot rod factors be used to conservatively estimate fractional gas release.

FIGRO calculates the amount of fission gas present in the gap on the basis of input depletion value. Thus, for calculations at a point along the rod axis, input should be modified to account for rod axial average depletion. The simplest method to account for this effect, without disturbing the rest of the calculation, is to divide the parameter B in Equation (20) by the ratio of input depletion to rod average depletion. Thus, for calculations at the peak depletion location, the parameter B should be divided by the rod peak-to-average depletion.

An additional effect, to be accounted for in binary fuel materials, is the effect of fuel inhomogeneity on gas release. This can be characterized as the presence of local clumps of a high concentration of fissile material (e.g., UO_2) within the matrix of the fuel composition. Since the fissioning rate within these clumps will be higher than that of the surrounding matrix, thus operating at a higher temperature and attaining a greater depletion, a larger fraction of fission gas release would be expected for an inhomogeneous, as compared to a homogeneous, pellet containing the same number of fissile atoms. Fractional gas release from an inhomogeneous pellet can be computed as follows.

The ratio of the amount of gas released from a pellet containing clumps to that of a homogeneous pellet containing the same number of fissile atoms can be expressed as

$$R = \frac{B_I \dot{F}_I V_I + B_M \dot{F}_M V_M}{B_H \dot{F}_H V_H} \quad , \quad (22)$$

where subscripts I, M, H refer to the inhomogeneities, the matrix surrounding the clumps (assuming uniform distribution of fissile material within the matrix), and a homogeneous pellet respectively, and

$\dot{F}$ = fission rate

V = volume

B = fraction of fission gases released.

Since the fissile content and the total volume of an inhomogeneous and a homogeneous pellet are equal,

$$\rho_I V_I W_I + \rho_M V_M W_M = \rho_H V_H W_H \quad (23)$$

and

$$V_I + V_M = V_H \quad , \quad (24)$$

where

ρ = density

W = weight fraction of fissile oxide material.

We now make the following assumptions:

- (1) Fissioning rate is proportional to fissile atom content

$$\frac{\dot{F}_I}{\dot{F}_H} = \frac{\rho_I W_I}{\rho_H W_H} \quad (25a)$$

and

$$\frac{\dot{F}_M}{\dot{F}_H} = \frac{\rho_M W_M}{\rho_H W_H} \quad , \quad (25b)$$

- (2) The fraction of gas released from a homogeneous pellet is equal to that released from the matrix surrounding the clumps:

$$B_M = B_H \quad . \quad (26)$$

Let B_p equal the fraction of gas released from a pellet containing inhomogeneities. Then

$$B_p = R P_H \quad . \quad (27)$$

Combining Equations (22) to (27) we obtain

$$B_p = B_H + \frac{\rho_I V_I W_I}{\rho_H V_H W_H} (B_I - B_H) \quad . \quad (28)$$

For design purposes, the following conservative assumptions are made:

- (a) The fuel clumps are 100-percent dense in fissile material or ($W_I = 1.0$).
(b) The fuel clumps release 100 percent of the fission gas ($B_I = 1.0$).

Equation (28) can then be rewritten as

$$B_p = B_H + \frac{\rho_I}{\rho_H W_H} (1 - B_H) \frac{V_I}{V_H} \quad . \quad (29)$$

Since specification limits are ordinarily based on $\frac{V_I}{V_H}$, Equation (29) can be evaluated with B_H calculated, based on the procedure discussed on Page 26.

Standard

$F_1 = 0.33$ for U^{233} fuel, 0.3 for U^{235} fuel

$F_2 = \frac{\text{nominal fuel} - \text{clad gap volume}}{\text{nominal fuel} - \text{clad gap volume} + \text{minimum plenum volume}}$: design

$F_2 =$ as-fabricated measurements: best estimate

$F_3 =$ value obtained using Equation (29) divided by ratio of input depletion to rod average depletion: design

$F_3 =$ to be determined for specific conditions of temperature, time history, rod average depletion, and fuel inhomogeneity: best estimate.

d. Coolant, Corrosion Film, and Crud

Symbols F_2, F_3, F_4

Card 200

Words 2, 3, and 4

$F_2 = h_f$, clad surface film coefficient (Btu/hr-ft²-°F)

$F_3 = T_W$, coolant temperature, degrees F

$F_4 = P_e$, external system pressure, psia.

Temperature rise across the surface film is calculated from the subcooled or Jens-Lottes correlation as follows:

$$T_s = \text{Minimum} \left\{ \begin{array}{l} T_W + \frac{\phi_s}{h_f} \\ T_{\text{sat}} + \frac{60 \left(\frac{\phi_s}{10^6} \right)^{1/4}}{\exp(P_e/900)} \end{array} \right. , \quad (30)$$

where

$T_s =$ clad surface temperature, degrees F

$\phi_s =$ clad surface heat flux, (Btu/hr-ft²)

$h_f =$ clad surface film coefficient, (Btu/hr-ft²-°F)

$T_{\text{sat}} =$ saturation temperature of water at pressure P_e

$P_e =$ external system pressure, psia.

Analytic Procedure

For irradiation test analyses, best estimate values of F_2 , F_3 , and F_4 should be utilized. To maximize temperature, for design purposes, clad surface temperature should be set at local boiling for the maximum expected coolant pressure plus an allowance for long time crud and corrosion effects. This can be accomplished by inputs of a fictitious coolant temperature, equivalent to the clad surface temperature, and an essentially infinite surface film coefficient.

The corrosion of Zircaloy in water can be evaluated using curve fits to data available in the literature. The temperature rise across the corrosion film can be computed utilizing a value of 0.79 Btu/hr-ft-°F for the thermal conductivity of ZrO_2 . The user should calculate the temperature rise across the corrosion film for the specific condition of heat flux and time. Since oxide film buildup on Zircaloy is controlled by the temperature at the metal-oxide interface, any increase in the rate controlling temperature will increase the amount of corrosion. Thus, the insulating characteristics of crud must be factored into the calculation as well as an increase in the corrosion temperature due to bulk or local boiling according to the Jens-Lottes correlation. Corrosion film thickness calculations, therefore, should reflect as increases in the coolant temperature, both the effect of crud buildup and local boiling. Suitable factors to account for the effects of irradiation and material and test variability should be applied.

For design calculations, the temperature rise across the crud and corrosion film should be assumed to be an increase over the Jens-Lottes correlation. Therefore, it is recommended that the user input a fictitiously high system pressure to force the program to calculate a surface temperature in excess of that given by the Jens-Lottes correlation at the actual system pressure.

Metallographic examination of irradiation test fuel elements has revealed a thin layer of ZrO_2 (gray phase) on the inner clad surface of a number of samples (References 20 and 21). This gray phase, ranging in thickness from 4 to 8 microns (0.00015 to 0.00031 inch) has been observed on the internal surface of non-defected as well as defected and failed fuel elements. The oxide films were observed to be continuous on the internal circumference of rods in which pellet and clad were in contact and discontinuous around the circumference of rods having discontinuous areas of contact. The internal oxide film was not present on the clad inner surface of rods with no fuel - clad contact. The source

of the oxygen within the rod, to explain this phenomenon, has been attributed to the oxygen released as a result of fission or during formation of non-stoichiometric oxide states.

At present, no analytical procedure to predict the rate of formation of an internal film has been developed. Based on the evidence that (1) the internal film has been observed only in rods having intimate fuel - clad contact, and (2) the film thickness has not exceeded 8 microns (0.00031 inch) even in rods exceeding 15×10^{20} f/cc, the following procedure to account for the effect of the internal corrosion film on fuel element temperatures is suggested.

In any FIGRO calculation in which fuel-clad contact is predicted, the assumption should be made that a ZrO_2 film of 0.0005 inch is present at the clad inner surface. The temperature rise across this film is calculated by

$$\Delta T_{\text{film}} = \frac{\phi_c \left(\frac{r_c}{r_i} \right) (t)}{k_z}, \quad (31)$$

where

ϕ_c = clad surface heat flux (Btu/hr-ft²)

r_c = clad outer radius

r_i = clad inner radius

t = oxide film thickness, feet = 4.17×10^{-5} feet

k_z = thermal conductivity of ZrO_2 = 0.79 Btu/hr-ft-°F.

Thus, for a heat flux of 500,000 on the clad inner surface, a temperature rise of 26°F would be calculated. Since the presence of ZrO_2 on the clad inner surface does not affect the temperature rise across the cladding, the temperature rise calculated across the inner ZrO_2 film should be added to fuel temperatures only.

Standard

$$F_2 = \sim 10^{10}$$

F_3 = local boiling plus allowances for crud and corrosion

$$F_4 = \sim 2500 \text{ psi.}$$

4. Input Forcing Functions

Symbol X_1

Card 100

Word 1

$X_1 = 0$, clad surface heat flux to be specified

$X_1 = 1$, fuel center temperature to be specified.

This option determines whether the forcing function is to be the clad surface heat flux or fuel center temperature (in which case a search is made for the corresponding clad surface heat flux).

Analytic Procedure

Ordinarily the heat flux is supplied. However, either option may be used in both best estimate and design procedures when required. For example, fuel temperature may be the more appropriate quantity in an analysis of an irradiated specimen when, after metallurgical examination, some metallurgical temperature "marker" (melting, coring, columnar grain growth, etc.) is observed. In the design procedure the heat flux to central melting can be calculated as a function of depletion by input of the melting temperature as a function of depletion.

Symbol F_1

Card 200

Word 1

$$F_1 = \begin{cases} \text{clad surface heat flux} \times 10^{-6} \text{ (Btu/hr-ft}^2\text{)}, & \text{if} \\ X_1 = 0 \text{ on Card 100} \\ \text{temperature (F) at fuel center,} & \text{if } X_1 = 1 \text{ on Card 100.} \end{cases}$$

Analytic Procedure

To maximize temperature, for design purposes, clad surface heat flux should be input, including all applicable peaking and overpower factors. Examples of such peaking and overpower factors are:

- (1) Off-nominal fuel loading.
- (2) Off-equilibrium xenon effects.
- (3) Off-nominal reactivity effects (control rod position).
- (4) Steady state overpower (tolerance on full power, instrument error, uncertainties in local power, etc.).

In the calculation requiring temperature input (e.g., computing heat flux to central melting) the lowest limiting temperature value considering uncertainties should be specified.

$X_1 = 0$, radial power shape described by $I_0(K_r)$

$X_1 = 1$, radial power shape described as piecewise linear function of radius.

FIGRO provides for the description of nonuniform heat generation in the fuel as either a Bessel function shape, $I_0(Kr)$, or as a piecewise linear function of radius with a maximum of ten radial points specified.

Analytic Procedure

Nonuniform radial power distribution (self-shielding) can have significant effect on fuel temperatures. The sensitivity of fuel temperature to radial power shape is a function of fuel loading and rod diameter. Therefore, the radial power shape is a function of irradiation and will vary as fuel depletes (and as fuel is created in a breeder). The variation of radial power distribution with fuel loading can be adequately calculated by existing nuclear design tools. Thus, in general, a radial power shape should be described. It has been found that utilization of a piecewise linear functional relationship to describe the radial power profile provides greater generality than the Bessel function shape. Accordingly, Option 1 is preferred.

Standard

Design:	}	$X_1 = 1$.
Best Estimate:		

The next two cards deal with the description of the radial power shape.

Symbols $F_{11}, F_{12}, F_{21}, F_{22}, \dots, F_{n1}, F_{n2}$ Cards 1050 to 1059 Words 1 to 20

$F_{i1} = f_i(r)$, radial power shape factor (dimensionless) at

$F_{i2} = r_i$, radial position (inches), $i = 1, 2, 3, \dots, 10$.

From 2 to 10 pairs of values may be supplied. These shape factors define the radial power shape of heat generation rate due to fuel self-shielding of slow or thermal neutrons.

Standard

Obtained from nuclear calculations.

F_1 = fraction of heat generated in the fuel by gamma heating

F_2 = fraction of heat generated in the fuel by fast or epithermal neutron fissioning.

The heat generated in the fuel by gamma heating and fast or epithermal neutron fissioning is assumed to be uniform (independent of radius). The total heat generation rate is computed as a linear combination of the $f_1(r)$ values on Card 1050 and the two values on Card 1060. The program internally normalizes the heat generation shape to give the correct value of surface heat flux.

Standard

Obtained from nuclear calculations.

Symbol F_6

Card 200

Word 6

F_6 = compartment depletion, 10^{20} fissions/cc, based on the volume internal to the clad.

Analytic Procedure

The calculation of temperature in FIGRO is performed at a specified depletion. Thus, to perform a lifetime study, it is necessary to submit several cases at different depletions. This is handled simply in FIGRO by supplying only the changes to the initial case. Thus, a heat flux-depletion varying lifetime study would require only the addition of a 200 card at several specified depletions to the initial deck. For design, depletion must be input assuming all applicable factors as described in Section III.B.2.c dealing with surface heat flux.

Symbol F_5

Card 300

Word 5

$F_5 = \theta_c$, fraction of total heat generation, Btu/hr, of the fuel element generated in the cladding.

Analytic Procedure

Provision is made in the FIGRO program for gamma heat generation in the cladding. Generally, this value is a function of reactor position and power density. Nuclear design calculational techniques are available to determine gamma heating at the appropriate location.

Standard

Design: }
Best Estimate: } Obtained from nuclear calculations.

Symbol F_4

Card 1200

Word 4

F_4 = fuel initial porosity (fractional).

Analytic Procedure

For design purposes, to maximize temperature, the largest porosity allowable within specifications should be input, since thermal conductivity is reduced with increased porosity. For other design criteria, fuel porosity should be input at the most limiting condition within manufacturing tolerances.

Symbols $F_1, \dots, F_7$

Card 1400

Words 1 to 7

F_1 = minimum allowable inside fuel radius, inches (applicable to annular pellets only)

F_2 = maximum allowable outside fuel radius, inches

F_3 = maximum allowable axial fuel swelling, fractional

F_4 = minimum allowable fuel porosity, fractional

$F_5 = A = \frac{\text{fuel swelling accommodated in fuel porosity}}{\text{total calculated fuel swelling}}$

$F_6 = B = \frac{\text{swelling accommodated in axial dimen. incr.}}{(\text{total calculated swelling}) - (\text{swelling accommodated in fuel porosity})}$

$F_7 = C = \frac{\text{swelling accommodated in radial increase}}{(\text{total calculated swelling}) - (\text{swelling accommodated in porosity}) - (\text{swelling accommodated in axial increase})}$

The preceding seven parameters specify the mode in which the total calculated fuel swelling is subdivided into components which alter the porosity and dimensions of the fuel region. Maximum flexibility is available in the choice of these parameters such that 0 to 100 percent of the computed swelling may be accommodated in any one or in any combination of the various components. With proper specification of F_5 , F_6 , and F_7 it is possible to have porosity and dimensional changes up to the limits specified by parameters F_1 , F_2 , F_3 , and F_4 . Specification of these parameters may be based on (1) assumptions which result

in conservative predictions of temperature and depletion capability, (2) best fit values to experimental observation, or (3) fitted values to duplicate more sophisticated structural analysis calculational models such as CYGRO (Reference 6).

Analytic Procedure

Fuel swelling accommodation can significantly affect fuel temperature due to porosity changes, radial heat path increases, and fuel - clad gap closure. Since these effects are competing, no clear-cut conservative prescription could be developed. Work was undertaken to obtain "best fit" values of the above parameters to CYGRO-1 calculations; that is, result in fuel pellet porosity and dimensional changes in reasonable agreement with CYGRO-1 calculations of exactly similar fuel element. These values are reported below and are suggested for design. Since FIGRO does not account for clad diameter shrinkage due to clad creep under external pressure, fuel temperatures calculated in FIGRO using these parameters will be somewhat higher than would be predicted if the effect of clad creep on fuel-clad gap thickness were accurately represented.

For analysis of irradiation test specimens the user should determine values of the parameters that result in best fit to measurements, if available.

Standard

Design: $F_1 = 0.0$

$F_2 =$ clad inside radius

$F_3 = 0.25$

$F_4 = 0.0$

$F_5 = -1.0$

$F_6 = 0.25$

$F_7 = 1.0$

B. Plenum Region

Many fuel rod designs incorporate a plenum region above the fuel stack which has the functions of providing void volume for collection of released fission gases, thus reducing clad stresses, and additionally providing room for fuel length increases due to thermal expansion and fuel swelling. A coiled spring is often incorporated within the plenum to prevent damage to the fuel stack during shipment and to prevent the opening of gaps between fuel pellets during operation.

The latter function assumes greater significance if non-free-standing tubing is employed for cladding. In this case an internal support sleeve is often incorporated to support the cladding in the plenum region.

The calculation of clad and plenum spring temperatures in the plenum region of the fuel element is important in predicting clad and spring behavior since performance adequacy in this region is dependent on metal temperatures. The calculational procedure developed in this section considers both radial and axial flow of heat. Axial heat conduction has been neglected in calculating temperatures in the fueled region of the fuel element since the axial gradients are small relative to the radial gradients. However, axial flow of heat is of greater consequence in the plenum region since one end of the plenum spring is in contact with a fuel pellet in which heat is being generated and the internal heat generation in the metal, due to gamma heating, is small relative to the fueled region. The presence of fission gases in the plenum region surrounding the spring and the possible presence of a clad supporting sleeve in the plenum region further complicates the calculation. However, since internal heat generation in the plenum region and in the top fuel pellet is relatively small, simplifying assumptions can be made. The calculational procedure including all simplifying assumptions and suggested properties are described herewith.

1. Axial Heat Flow

Figure 3. Plenum Spring Schematic

Consider Figure 3, in which the plenum spring is idealized as a long rod in contact with the top fuel pellet at one end and the top end cap at the

other. Let t_0 = temperature at $x = 0$ and t_e = temperature of the environment (fission gas surrounding spring). Then, for steady state flow of heat,

$$q_1 + dq_3 = q_2 + dq_4, \quad (32)$$

where

q_1 = incoming heat at $x = x$

q_2 = outgoing heat at $x = x + dx$

dq_3 = internal heat generated in volume Adx

dq_4 = heat lost to environment from surface Cdx .

Thus,

$$-kA \frac{dt}{dx} + q''' Adx = -kA \left(\frac{dt}{dx} - \frac{d^2t}{dx^2} dx \right) + hC(t - t_e)dx, \quad (33)$$

where

k = thermal conductivity of spring

h = surface coefficient of heat transfer

A = cross sectional area of rod = πr_s^2

C = circumference of cross section = $2\pi r_s$

q''' = volumetric heat generation rate in spring

r_s = spring wire radius.

Letting $\theta = t - t_e$ and $m^2 = \frac{hC}{kA} = \frac{2h}{kr_s}$, Equation (33) reduces to

$$\frac{d^2\theta}{dx^2} = m^2\theta - \frac{q'''}{k}. \quad (34)$$

Assuming q''' is independent of x , a general solution to Equation (34) is given by

$$\theta = C_1 e^{-mx} + C_2 e^{mx} + \frac{q'''}{km^2}, \quad (35)$$

where C_1 and C_2 are constants of integration which can be determined from the boundary conditions.

Thus,

$$C_1 = \frac{\frac{q'''}{km^2} + Me^{mL}}{e^{mL} - e^{-mL}} \quad (36)$$

and

$$C_2 = \frac{\left[\frac{q'''}{km^2} + Me^{-mL} \right]}{e^{mL} - e^{-mL}}, \quad (37)$$

where $M = t_o - t_e - \frac{q'''}{2}$ and L = unwound length of spring.

Thus, the spring temperature at any axial point can be calculated from Equations (35), (36), and (37).

For design calculations, the following values for thermal properties are suggested:

a. t_o ; Temperature at Spring - Top Fuel Pellet Interface. The temperature distribution in the top fuel pellet at any time in life can be obtained from FIGRO calculations using the appropriate heat flux obtained from nuclear calculations and including all applicable peaking factors. As recommended in Section III.A.4, manufacturing tolerances should be stacked so as to obtain the maximum temperature (i.e., maximum fuel-clad gap, minimum fuel density). Calculations should be performed for the rod having the largest average fuel depletion in the region so as to maximize the concentration of fission gases in the gap.

For design purposes, it is suggested that t_o be set equal to the temperature at that radial point in the top pellet corresponding to maximum displacement of the spring relative to the pellet. That is, assume an eccentric pellet and minimum OD offset to the clad ID and the minimum spring coil OD offset 180 degrees relative to the top fuel pellet.

b. t_e ; Temperature of the Spring Environment (Gas Mixture Surrounding Spring). The temperature of the gas mixture surrounding the spring will vary with the relative concentration of fission gas, and this is a function of rod depletion, fuel temperatures, and time. The thermal conductivity of the gas mixture at any time in life can be obtained from FIGRO calculations performed for the fuel element seeing the largest average fuel depletion. Temperature of the gas mixture calculated by FIGRO for the top fuel pellet should be assumed axially constant. This will minimize spring heat losses to the environment and thus maximize spring temperatures.

c. q''' ; Internal Heat Generation Rate in Spring. The spring internal heat generation, due to gamma heating, can be obtained from nuclear calculations. For design purposes, to maximize temperatures, the largest value calculated including all applicable peaking factors should be assumed axially constant.

d. h ; Surface Coefficient of Heat Transfer. Free convection in cylindrical gas layers has been investigated and found to be negligible for small

annuli. Thus, the surface coefficient of heat transfer can be evaluated considering conduction only as follows:

$$t + t_e = \frac{q''' r_o}{2 h} = \frac{q''' r_o}{2 H_g \frac{r_o}{r_g}} \quad (38)$$

or

$$\frac{r_o H_g}{r_g},$$

where

- r_o = spring coil outer radius
- r_g = radius of gap = $r_o + \frac{1}{2} (r_i - r_o)$
- r_i = inner radius of clad or support sleeve
- H_g = gap heat conductance.

The gap heat conductance can be obtained from radial heat flow calculations described in the succeeding section.

2. Radial Heat Flow

Temperature distributions in clad, support sleeve (if present), gas mixture, and plenum spring in the plenum region of the fuel element can be calculated considering radial heat flow from a knowledge of heat generation rates in the metal, thermal conductivity of the metal and gas mixture, and differential thermal expansion of spring, support sleeve and clad. Thus, the FIGRO program can be adapted to perform the desired radial calculation idealizing the spring coil as an annular ring. Suggested values for thermal and physical properties are described below only for input parameters which are changed from those given for the fueled region of the element. Input referring to oxide properties such as fuel swelling should be suppressed by appropriate input.

a. Geometry. For fuel elements containing both support sleeve and spring in the plenum region, the two-radial zone option in FIGRO should be used. This is indicated by $X_2 = 2$ on Card 100. The dimensions of the support sleeve are input on Card 1200 and the spring coil dimensions are input on Card 2200. For elements containing only a spring, the one-radial zone option should be used ($X_2 = 1$ on Card 100). Spring coil dimensions are then input on Card 1200. Clad, support sleeve, and spring coil dimensions should be input within manufacturing tolerances to maximize temperature rise in the metal.

b. Thermal and Physical Properties. For elements containing only a spring, spring thermal conductivity is input on Card 1101. For elements

incorporating a support sleeve as well as a spring, support sleeve thermal conductivity is input on Card 1101 and spring conductivity on Card 2101. Thermal expansion of sleeve or spring is input on Card 1610. Thermal conductivity and thermal expansion functional relationships used in FIGRO can be fit to data for the appropriate spring and support sleeve material.

Gas conductivity will be internally calculated in FIGRO based on user input of rod average depletion and fractional gas release for the rod axial average depletion (for the most highly depleted rod).

c. Input Forcing Functions. Fuel element surface heat flux in the plenum region should be determined by the user from nuclear calculations of gamma heating rates in the clad, support sleeve, and spring including all applicable peaking factors. Calculations should be performed for the axial slice in which the highest heat generation rates are calculated.

Spring temperatures obtained from both radial and axial heat flow calculations should be compared and the most limiting temperature used in evaluating performance adequacy.

IV. EFFECTS OF ECCENTRICITY OF CLAD AND FUEL-CLAD GAP, CLAD OVALITY, AND PELLET CIRCUMFERENTIAL CRACKING

A. Eccentricity and Ovality

Since the FIGRO program considers only one-dimensional heat flow, the effects of eccentricity of clad and fuel - clad gap and clad ovality must be obtained using two-dimensional heat conduction models. Calculations were performed by the author in two-dimensional cylindrical geometry. Eccentricity of clad thickness was represented by input of an azimuthally-varying clad thermal conductivity and ovality and fuel - clad gap eccentricity was represented by an azimuthally-varying gas conductivity.

Results indicate negligible changes in fuel temperature due to ovality and eccentricity for displacements up to 0.020 inch. The maximum fuel temperature is displaced slightly from the center (~0.005 inch) but is not greater (within the convergence of the calculation) than the symmetric case. Fuel volume averaged temperatures also differ negligibly from the symmetric case. This is explained by the fact that where heat flux is greater than average (eccentric pellet in contact with clad) the interface conductance is high, minimizing the temperature rise. Conversely, 180 degrees away, where the fuel - clad gap is at a maximum and gap conductance is low, the heat flux is below the average.

Cladding temperatures are somewhat sensitive to ovality and eccentricity due to the circumferentially-varying heat flux. However, since Zircaloy has relatively high thermal conductivity, circumferential heat conduction through the cladding tends to minimize azimuthal temperature gradients. Thus, for the worst case of eccentricity examined (~ 0.020 inch), the clad radial average temperature at the hottest azimuthal point (fuel and clad in contact) was less than 10F greater than the symmetric case. Where the fuel - clad gap is at a maximum, clad temperature is lower than average.

Based on these results, it appears that no correction need be applied to the fuel and clad temperatures calculated using the procedure described in this report to account for ovality and eccentricity effects for manufacturing tolerances which limit fuel pellet eccentricity to 0.020 inch. For designs in which larger displacements are possible, specific two-dimensional calculations should be performed to determine eccentricity effects on temperature.

B. Pellet Circumferential Cracking

The presence of a crack in the fuel pellet, perpendicular to the flow of heat, would be expected to increase fuel temperatures inbound of the crack. The author has found that an arbitrary increase of 200F to account for pellet circumferential cracking is reasonably conservative to include in design calculations. Thus, an allowance of 200F should be added to the maximum fuel temperatures calculated using the procedure described in this report and all fuel temperatures reported in design evaluations should include this allowance.

V. INTERPRETATION OF OUTPUT

FIGRO output consists of two pages per case for the reduced output option or three pages per case for the full output option. This is controlled by Word 2 on Card 1100.

The first page of output consists of a listing of the input deck. The most pertinent output appears on the second page; clad surface heat flux and the temperatures at the inside and outside of the clad and fuel regions are edited as computed before any fuel swelling. After this edit, the heat conduction and fuel swelling equations are solved simultaneously. The resulting temperatures at the inside and outside of the clad and fuel regions, new dimensions, calculated fuel-clad gap heat transfer coefficient, fractional fuel swelling, residual porosity, heat generation and fissioning rates, and fuel depletion are then edited.

The third output page, which is optional, consists of the following quantities.

- (1) The value of fuel porosity used in the thermal conductivity multiplier.
- (2) A table of thermal conductivity, (Btu/hr-ft-°F), and

$$\int_0^T kdT$$

(Btu/hr-ft and watts/cm) versus temperature from 0 to 7000F at 200 degree intervals.

- (3) The temperature, in degrees F, and

$$\int_{T_s}^{T_i} kdT$$

(watts/cm) at each of the equally spaced radial boundaries which define the calculational rings. T_s is the fuel surface temperature.

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Appendix A. Guide to FIGRO Input Requirements

Card No.	Word No.	Parameter	Page No.
100	1	Surface heat flux or peak temperature option	34
100	2	One or two radial zones of fuel	5
100	3	Fuel swelling model option	8
100	4	Solid fuel swelling coefficient option	9
100	5	Fission gas release option	10
100	6	Input as 0.0	--
150	1	Radial power shape option	35
200	1	Surface heat flux or peak temperature	34
200	2	Clad surface film coefficient	31
200	3	Coolant temperature	31
200	4	Coolant pressure	31
200	5	Fuel hydrostatic pressure	10
200	6	Fuel depletion	36
300	1	Clad inner radius	5
300	2	Clad outer radius	5
300	3	Clad axial length	5
300	4	Clad thermal conductivity option	6
300	5	Fraction of heat generated in clad	6
301, 302 and 303	1 to 10	Clad thermal conductivity versus temperature table	7
400	1	Solid fuel swelling coefficient	10
500	1 to 4	Fission gas release constants	11
600	1 to 3	Clad thermal expansion constants	7
700	1	Clad surface emissivity	20
700	2	Fuel surface emissivity	20
800 and 801	1 to 9	Gas thermal conductivity constants	23
1000	1	Temperature jump distance of initial fill gas	20
1000	2	Temperature jump distance of fission gas	20
1000	3	Clad surface roughness	21
1000	4	Fuel surface roughness	21
1000	5	Fuel - clad contact pressure	22

Guide to FIGRO Input Requirements (Cont)

Card No.	Word No.	Parameter	Page No.
1000	6	Meyer hardness of softer solid	22
1000	7	Fuel - clad contact coefficient	21
1050 to 1059	1 to 20	Fuel heat generation versus radius table	35
1060	1	Gamma heating fraction	36
1060	2	Fast fission heating fraction	36
1100	1	Porosity correction factor option	13
1100	2	Output option	4
1101 to 1103	1 to 13	Fuel thermal conductivity constants	14
1150	1	Pore shape factor	13
1200	1	Fuel inner radius	6
1200	2	Fuel outer radius	6
1200	3	Fuel axial length	6
1200	4	Fuel initial porosity	37
1300	1	Number of fuel mesh intervals	3
1400	1 to 7	Fuel swelling accomodation factors	37
1500	1	User guess of peak temperature	--
1600	1	Fuel thermal expansion option	16
1610	1 to 3	Fuel thermal expansion constants	16
1700	1	Gas atoms produced per fission event	25
1700	2	Fission gas release fraction	25
1700	3	Ratio of fuel - clad gap volume to total void volume	25

APPENDIX B
SAMPLE PROBLEM

LISTING OF INPUT DATA FOR CASE 1

FIGRO U GOLDB P 04/10/69 CCCF233 PAGE 1

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      * FIGRO SAMPLE PROBLEM FOR WAPP-TM-757
      * DESIGN PROCEDURE FOR THOP + 10W/O UNO 95 PC TD
0001  100.0,1.0,1.2,0
0002  200.0,3.1,+10.650,.2500,.2000,.2.0
0003  300.0,21.0,25,1.0,5.0,0.01E
0004  301.8,69,600.0,8.88,650.9,08,700.9,28,750.9,49,800.
0005  400.0,0025
0006  500.4100.0,0.0,0.5.0
0007  600.6.0-5,5.14-6,3,80-q
0008  800.2.636,0.856,-.0265,-.46188,0.248,1.468,0.825,-0.104,-4.3538
0009  1000.244.0,21.8,30.0,40.0,2000.1.2+5,1.0
0010  1100.3,0
0011  1101.1894.7,648.4,3.24352,0.0,0.02112,0.0
0012  1150.1,55
0013  1200.0,0.0,0.2075,1.0,0.05
0014  1300.10
0015  1400.0,0,0,21.0,25.0,0.-1.0,0.25,1.0
0016  1500.3000.0
0017  1600.1
0018  1610.-2.23-4.9,42-4.0,706-q
0019  1700.0,33,0,25.0,075

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FIGRO SAMPLE PROBLEM FOR WAPD-TM-7E7

FIGRO U GOLDB P 04/10/69 CCCF233 PAGE 2

*FIGRO - CDC 6600 VERSION 05-08-67

FOR P(PRIA) = 2500.0 JENS=10TTFS SHRF. TEMP(F) = 670.9

DRF-GROWTH TEMP DIST FOR FLUX(1.E-4*8/HR-FT2) = .30000

ZONE	FUEL		CLAD	
POSITION	R2	R3	R4	R5
DIMENSION(IN)-ORIG	0.	.20750	.21000	.25000
TEMPERATURE(F)	6000.9	4802.9	768.4	650.0
CLAD-FUEL GAP HEAT TRA. COEFF. (B/HR-FT2-DEG F)	94.8			

-- FINAL EDIT -- FLUX(1.E-4*8/HR-FT2) = .30000

ZONE	FUEL		CLAD	
POSITION	R2	R3	R4	R5
DIMENSION(IN)-NEW	0.	.21000	.21000	.25000
TEMPERATURE(F)	3082.8	983.5	768.4	650.0
CLAD-FUEL GAP HEAT TRA. COEFF. (B/HR-FT2-DEG F)	1634.1			

TOTAL FUEL GROWTH

FRACT OF ORIG VOL .01380

EXCESS FUEL GROWTH

FRACT OF ORIG VOL 0.

POROSITY

FRACT OF ORIG VOL .05000

BETA

1.550

LENGTH(IN)-NEW

1.003

1.000

HEAT GEN. RATE-NEW

BTU/HR-FT3 40065812+02

14473913+07

KW/LITER 41466123+02

15184770+02

DEPLETION

1.E-20*FISS/CC OF
DENSE FUEL

2.156

FISSION RATE

1.E-13*FISS/CC OF
DENSE FUEL-SEC

1.409

MAX. FUEL TEMP. = 3082.8 EXCEEDS 3000.0

FIGRO SAMPLE PROBLEM FOR WARD-TM-7E7

FIGRO U GOLDB P 04/10/69 CCCF233 PAGE 3

*FIGRO - CDC 6600 VERSION 05-08-67

EDIT OF THERMAL PROPERTIES AND TEMPERATURES

T=TEMP(F), K=THERMAL CONDUCTIVITY(R/HR-FT-DEG F), IK=INTEGRAL OF K FROM 0 TO T, AND P=POROSITY IN $(1-P)/(1+RTA*P)$.

****RESULTS FOR ZONE 1****

D= .0430

T	K	IK	IK(W/CM)	T	K	IK	IK(W/CM)	T	K	IK	IK(W/CM)
0.	2.3205	0.	0.	2400.0	1.2704	4576.9	44.009	4800.0	.7466	6891.3	66.263
200.0	2.4939	486.5	4.677	2600.0	1.2018	4924.0	46.385	5000.0	.7215	7038.1	67.674
400.0	2.4565	982.7	9.459	2800.0	1.1399	5058.1	48.635	5200.0	.6979	7180.0	69.039
600.0	2.3319	1463.4	14.071	3000.0	1.0837	5280.3	50.773	5400.0	.6758	7317.4	70.359
800.0	2.1796	1914.7	18.411	3200.0	1.0325	5491.9	52.807	5600.0	.6550	7450.4	71.639
1000.0	2.0260	2335.2	22.453	3400.0	.9858	5693.7	54.747	5800.0	.6355	7579.5	72.879
1200.0	1.8817	2725.7	26.209	3600.0	.9430	5886.5	56.601	6000.0	.6170	7704.7	74.084
1400.0	1.7501	3088.7	29.690	3800.0	.9036	6071.1	58.376	6200.0	.5996	7826.4	75.253
1600.0	1.6317	3426.6	32.949	4000.0	.8673	6248.1	60.078	6400.0	.5832	7944.6	76.391
1800.0	1.5259	3742.2	35.983	4200.0	.8337	6418.2	61.713	6600.0	.5676	8059.7	77.497
2000.0	1.4312	4037.7	38.824	4400.0	.8026	6581.8	63.286	6800.0	.5528	8171.7	78.574
2200.0	1.3465	4315.4	41.494	4600.0	.7736	6739.3	64.801	6999.9	.5388	8280.9	79.624

TEMPERATURES IN ZONE 1 AT 11 EQUALLY SPACED NEW R VALUES, STARTING AT THE OUTSIDE SURFACE

983.5 1286.8 1587.0 1883.0 2162.7 2419.5 2645.4 2830.4 2968.4 3053.8 3082.8

INTEGRAL OF K FROM ZONE 1 SURFACE TEMP. TO THE ABOVE TEMP.S. AT THE NEW EQUALLY SPACED R VALUES IN W/CM

.000 5.604 10.618 15.043 18.877 22.122 24.776 26.841 28.316 29.201 29.495

END OF JOB, CASE RUN TIME= .023 (MIN)

***** END OF OUTPUT *****