**Fuel Rod and Clad Temperature Distribution Calculations: Comparative analysis using different gap conductivity models**

For this homework assignment, the FULTEMP2 (FUeL TEMPerature version 2) computer program will be used. FULTEMP2 calculates the fuel pellet and cladding temperature distribution considering variable fuel and cladding conductivities and using three different models for the gap heat transfer coefficient: Dean's; Ross and Stoute's; and Weisman and McDonald's models. The gas gap mixture properties are also calculated. The input consists of:

| | |
|---|---|
| HFILM: | Forced convection heat transfer coefficient (BTU/hr-ft$^2$-°F) |
| TBULK: | Local coolant temperature (°F) |
| PELD: | Fuel pellet diameter (inches) |
| RODD: | Fuel rod diameter (inches) |
| CT: | Clad thickness (inches) |
| ILQ: | Local linear heat rate (kW/ft) |
| AHE: | Mole fraction of Helium (fraction) |
| AXE: | Mole fraction of Xenon (fraction) |
| FDEP: | Flux depression factor (fraction) |
| HGAPM1: | Dean's model for pellet/cladding heat transfer coefficient |
| HGAPM2: | Ross and Stoute's model for pellet/cladding heat transfer coefficient |
| HGAPM3: | Weiman and McDonald's model for pellet/cladding heat transfer coefficient |
| XKMIX: | Mixture gas conductivity |
| TO: | Fuel pellet centerline |
| QVOL: | Volumetric heat generation rate (BTU/hr-ft$^3$) |

*Input for Dean's model:*

| | |
|---|---|
| PCON: | Contact pressure (psia) |
| ALPHA: | 0.6 for Zirc; 0.48 for Stainless steel |
| EM1: | Fuel Emissivity |
| EM2: | Cladding Emissivity |

AO: Empirical constant = 0.0905 $ft^{1/2}$

*Input for Ross and Stoute's model*

H: Meyer Hardness of soft material (psia) - $13\times10^4$ for stainless steel; $14.2\times10^4$ for Zirc

R1, R2: RMS roughness of pellet and cladding (micro inches)

*Input for Weisman and McDonald's model*

GAPD: Diametrical gap (inches)

The fuel rod specification is as follows:

| | |
|---|---|
| $UO_2$ Theoretical Density | 95% |
| Enrichment | 4.5% |
| Rod Outside Diameter | 0.422 inches |
| Clad Thickness | 0.024 inches |
| Pellet Roughness | $125\text{x}10^{-3}$ inches |
| Clad Roughness | $125\text{x}10^{-3}$ inches |
| Bulk Coolant Temperature | 585 $^o$F |
| Surface Heat Transfer Coefficient | 6500 BTU/hr-$ft^2$- $^o$F |
| Diametrical Gap | 0.002 inchess |

This homework consists of four parts as described hereafter.

**PART 1:** During the life of the fuel rod in the core, the gas pressure in the rod increases as fission products are released. The gaseous fission products will decrease the effective conductivity of the gas in the gap between the fuel pellet and cladding. *In Part 1, the objective is to investigate the change of the fuel heat rate limits with burnup.* The following gas compositions as function of burnup are to be used:

| **Burnup MWD/T** | **Mole fraction of He %** | **Mole fraction of Xe %** |
|---|---|---|
| 0 | 100.0 | 0.0 |
| 5000 | 98.0 | 2.0 |
| 7000 | 90.0 | 10.0 |
| 10000 | 83.0 | 17.0 |

| | | |
|---|---|---|
| 20000 | 73.0 | 27.0 |
| 40000 | 58.0 | 42.0 |
| 62000 | 41.0 | 59.0 |

The allowable peak heat rates for two gap heat transfer models, Dean's model and Ross and Stoute's model, as a function of burnup are to be determined using the thermal limit of 5000 $^{o}$F centerline fuel temperature.

To present your results:

1) Tabulate and plot the allowable peak heat rate as a function of burnup for the two gap conductance models.
2) Tabulate and plot the temperature distribution within the fuel rod at three burnup steps: 0; 20000; and 62000 MWD/T for the two gap conductance models.
3) Discuss results and give your conclusions.

**PART 2:** In the calculations performed in Part 1 you did not account for the possible pellet/cladding contact due to fission gases released at high burnups. *As a result of the pellet/cladding contact, the allowable peak linear heat rate will increase due to the better solid-to-solid surfaces heat transfer.*

The following contact pressure is to be assumed at high burnup:

| **Burnup MWD/T** | **Contact Pressure psia** |
|---|---|
| 20000 | 300 |
| 40000 | 800 |
| 62000 | 1400 |

Assume the same gas compositions as function of burnup as in Part 1.
Note that for the burnups above 20000 MWD/T, the gap input for FULTEMP2 is equal to zero.

For the burnups of 20000, 40000, and 62000 MWD/T, calculate the new allowable peak heat rate for the Dean's model and Ross and Stoute's model.

To present results:

1) Tabulate and plot the new allowable peak heat rates a function of burnup for the two gap conductance models.
2) Tabulate and plot the temperature distribution within the fuel rod at three burnup steps: 20000; 40000; and 62000 MWD/T for the two gap conductance models.
3) Discuss results and give your conclusions.

**PART 3:** Pellet and cladding relative roughness can affect the gap heat transfer coefficient and the resulting temperature rise across the gap. There is a manufacturing cost associated with making smoother pellet and cladding surfaces. However, there is maybe a gain in the allowable kW/ft if the surfaces are smoother.
*The allowable peak heat rate is to be determined for a very smooth fuel and cladding combination in which the clad roughness is 10 micro inches and pellet is 30 micro inches.* The calculation are to be repeated over the full burnup range as given in Part 1, but accounting for the contact pressure at high burnup.

To presents results:

1) Tabulate and plot the obtained allowable linear heat rates for very smooth pellet and clad surfaces (Dean's and Ross and Stoute's models).
2) Without accounting for the pellet/clad contact, tabulate and plot the temperature distribution within the fuel rod at three burnup steps: 0; 20000; and 62000 MWD/T (Dean's and Ross and Stoute's models).
3) With accounting for the pellet/clad contact, tabulate and plot the temperature distribution within the fuel rod at three burnup steps: 20000; 40000; and 62000 MWD/T (Dean's and Ross and Stoute's models).
4) Discuss results and give your conclusions.

**PART 4:** Provide overall conclusions.

## Appendix: Description of the Gap Conductance Models

The heat flow across the fuel rod gap is given as

$$q_s = \pi R L h_{gap}(T_s - T_{ci}) \text{ (Btu/hr)} \tag{1}$$

To solve Equation (1), an expression for the gap conductance, $h_{gap}$, is needed. For typical scoping calculations a value of $h_{gap}$ = 1000 Btu/hr-ft$^2$-$^\circ$F is normally assumed. However, for fuel rod design limits and postulated reactor accident condition, a calculational method for determining $h_{gap}$ must be used.

**Dean** examined all possible modes of heat transfer and found that the gap conductance was a result of:

1. Conduction across a gas film
2. Conduction between the fuel and clad at the points of contact
3. Radiation from the pellet to the clad

Under normal operating conditions, radiation can be ignored, however, it does become important during postulated accident conditions when the pellet surface temperatures is high.

Dean conducted experiments on a $UO_2$/Zr joint with different pressure loading and a prefilled gas to determine the gap conductivity. When there was no pressure being exerted between the fuel sample and cladding sample, the heat transfer is just the conduction across a gas film. In this case:

$$h_{gap} = \frac{k_g}{\text{Radius of Clad - Radius of Fuel} + 14.4\text{x}10^{-6}} \quad \frac{\text{Btu}}{\text{hr - ft}^2 - {}^oF} \tag{2}$$

where 14.4 x $10^{-6}$ is the effective RMS roughness difference between the two surfaces if one lies on the other with no contact pressure and the gap is essentially closed. In Equation (2), the radius of the clad and fuel are in feet. Normally for a LWR fuel at the beginning of life, with a solid pellet model, there is no hard clad-pellet contact. Therefore Equation (2) could be used for $h_{gap}$.

For the case where there is a pressure force exerted on the cladding by the fuel, the surface contact becomes of increasing importance. Dean found that he could correlate his data as

$$h_{gap} = \alpha P_{gc} + \frac{k_g}{14.4x10^{-6}}\left(\frac{Btu}{hr - ft^2 - {}^o\ F}\right) \tag{3}$$

where $\alpha$ = 0.6 for Zircaloy or $\alpha$ = 0.48 for stainless steel where no visible gap existed.

The $P_{gc}$ is the contact pressure due to the fuel expansion (which is caused by fission product swelling and thermal expansion as well as clad creep down on the fuel caused by the high external pressure in the primary coolant system). The contact conductance model is illustrated in Figure 1 and an example of the surface-to-surface conductance is shown in Figure 2. The greater the pressure, the harder $UO_2$ will penetrate either the zirconium or stainless steel clad. Since the zirconium is a softer material, the $UO_2$ pellet will try to penetrate further into the zirconium then the stainless. Hence the multiplier on the contact pressure term is larger.

$P_{gc}$ is calculated from an elastic analysis of a shrink fit of the cladding over the fuel. Therefore we must accurately know the fuel behavior. The thermal response of the fuel pin is dependent on the fuel rod burn up history and mechanical behavior of the fuel during its life. The reverse is also true; the mechanical behavior of the fuel pin is also related to its temperature history. Therefore, we have a coupled problem.

Another gap conductance model which has been used for design calculations when pellet/clad contact occurs is the **Ross and Stoute model**. They modeled the conductance as the summation of conductance across the gas film between contact points and conduction through the contact points, that is:

$$h_{gap} = h_{solid} + h_{gas-gap} \quad \left(\frac{Btu}{hr - ft^2 -^o F}\right)$$

Both $h_{solid}$ and $h_{gas\text{-}gap}$ are defined on the full interfacial surface area between the fuel surface and clad inside surface. The solid gap conductance is given as:

$$h_{solid} = \frac{k_m P_{c_t}}{\alpha_o R^{1/2} H} \qquad (4)$$

where

$k_m$ = harmonic mean conductivity of interface materials = $2k_1 k_2/(k_1+ k_2)$ (Btu/hr ft °F)

$Pc_t$ = contact pressure at interface (psia)

$\alpha_o$ = empirical constant = 0.0905 (ft $^{1/2}$)

R = root-mean-squre of contact materials surface roughness = $([R_1^2 + R_2^2 ] / 2)^{1/2}$, (ft)

H = Meyer hardness of softer material, (psi)

Typical values of H are 13 x $10^4$ psi for stainless steel and 14.2 x $10^4$ psi for Zircaloy. This type of a model is less empirical than Dean's model and can be extrapolated to other surface continuations. However, the empirical factor, $a_o$, still does tie the model to a specific data base. Ross and Stoute modeled the gas gap conduction between contact points at contact as:

$$h_{gas-gap} = \frac{k_g}{t + (g_1 + g_2)} \tag{5}$$

where

t = an effective gap between the contact points

$g_l$, $g_2$ = the effective temperature jump distance due to the temperature discontinuity in the very thin gas film.

The parameters $g_l$, $g_2$ modify the gas conductivity due to the deviation from continuity in the gas film. Values of $g_l$ and $g_2$ for different gases are given in Table 1.

The effective gas gap thickness, t, was empirically determined as:

$$t = C(R_1 + R_2) \tag{6}$$

where

$R_l$, $R_2$ = RMS of the roughness of the surfaces, and C was found to depend on the interface contact pressure.

Ross and Stoute fit the value of C to their data as:

$$C = 2.75 - 0.17x10^{-3} P_{ct} \tag{7}$$

where $P_{ct}$ is the interface contact pressure (psi). Therefore, the entire Ross and Stoute gap conductance model with pellet/clad contact becomes;

$$h_{gap} = \frac{k_m P_{ct}}{0.0905 R^{1/2} H} + \frac{k_g}{(2.75 - 1.7x10^{-3} P_{ct})(R_1 + R_2) + (g_1 + g_2)} \tag{8}$$

If pellet-clad contact does not exist and a gap does exist between the clad and pellet, then the conductance is given as Equation (2)

$UO_2$ fuel rods are initially pressurized with helium to help improve the gap conductance. BWR rods are usually prefilled from 40 to 100 psia, while PWR rods are prefilled between 100 to 350 psia. As the rods undergo fission and burnup, fission gases such as Xenon and Krypton are released in the $UO_2$ and diffuse to the gap. These lower conductivity gases decrease the overall gas conductivity in the pellet-clad gap with the result of decreasing the total gap conductance.

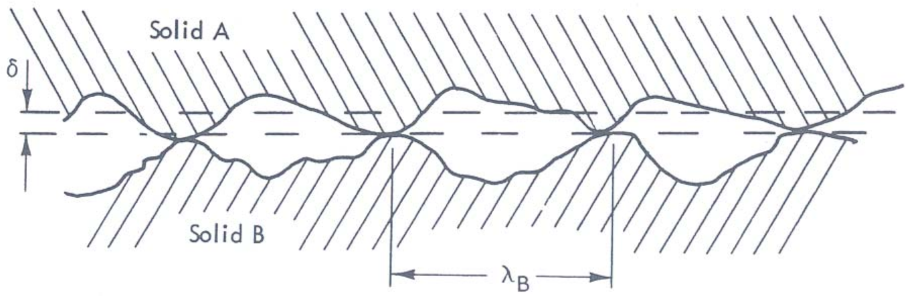


Figure 1. Contact Conductance Model

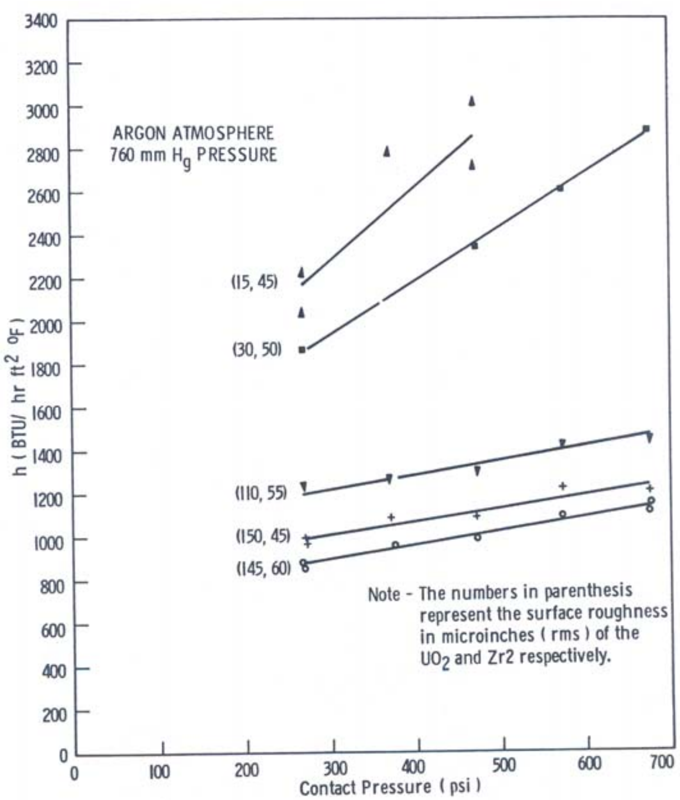


Figure 2. Uranium Dioxide-Zircaloy Contact Resistant Measured by Dean

Table 1. Values of Temperature Jump Distances for Various Gases

| Gas | $(g_1+g_2)$, cm | Temperature Range, $^oC$ |
|---|---|---|
| Helium | $10 \times 10^{-4}$ | 150-250 |
| Argon | $5 \times 10^{-4}$ | 180-320 |
| Krypton | $1 \times 10^{-4}$ | 180-330 |
| Xenon | $1 \times 10^{-4}$ | 180-330 |