COMBINED EFFECTS OF GRAPHITE DISCS AND CENTRAL HOLES ON PELLET TEMPERATURES IN CANDU FUEL

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ABSTRACT

Studies are currently underway to increase the average burnup in CANDU®* reactors while maintaining a low probability of fuel failure due to stress-corrosion cracking. This paper presents the results of a feasibility study on a design modification of the CANDU fuel involving annular UO_2 pellets separated by graphite discs. Slightly enriched uranium is used. The two-dimensional computer program FEAT was used to calculate the temperature distribution in the pellet, sheath, and graphite discs. The classical equation for steady-state non-linear conduction of heat is solved in the program by the finite element technique. A sensitivity analysis was carried out to examine the effects of fuel element linear power, fuel element burnup, pellet central hole diameter, and heat transfer coefficients at various interfaces of the pellet/sheath/disc; specifically, to investigate their impacts on fuel temperature distribution. The results confirm that, compared to the conventional solid pellets, annular pellets reduce the temperature at the pellet/disc interface. However, the annular pellets have little effect on the volume-average temperature of the pellet.

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* CANDU®: Canada Deuterium Uranium is a registered trademark of Atomic Energy of Canada Limited.

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INTRODUCTION

The average fuel burnup in CANDU reactors can be increased by using slightly enriched uranium. At high burnups, one consideration of fuel integrity involves stress-corrosion cracking due to pellet expansion and due to internal gas pressure. Previous studies [1] have shown that one way to enhance fuel integrity at high burnups is to use inter-pellet graphite discs. The graphite discs reduce the pellet temperature, which leads to less fission gas release, less pellet thermal expansion, and consequently less sheath stress.

The objective of the study reported in this paper was to investigate the influence of annular pellets on temperatures in graphite disc fuel.

In the past, graphite discs with solid and with annular pellets have been irradiated in test reactors [1]. The incentive to consider annular pellets was originally driven by a desire to prevent excessive chemical interaction of the graphite disc with UO_2 and/or Zircaloy. The interaction occurs only at very high temperatures [1,2]. Irradiations have shown that at high powers and burnups, the performance of graphite fuel continues to be excellent - despite some UO_2/graphite chemical interaction [1]. Nevertheless, annular pellets have been proposed in the past [1,3] for additional conservatism. The previous results have shown that the graphite discs, with solid or annular pellets, do reduce the pellet temperatures significantly [1,4].

Annular pellets have several competing influences on the performance of the fuel element. Firstly, the temperature is the highest at the centre of the pellet. Hence, the removal of UO_2 from the centre of the pellet tends to decrease the peak temperature in the pellet. Secondly, annular pellets provide open space at the centre of the pellet. This accommodates pellet swelling, which reduces sheath strains. Thirdly, annular pellets use less UO_2 to produce the same power. Hence the power density is higher in annular pellets, which tends to increase the temperatures. Fourthly, annular pellets reduce the throughput of UO_2, which reduces the total energy produced by the fuel bundle, and also increases the load on the fuelling machines. Thus, the pros of annular pellets need to be balanced against the cons. One place to start is to obtain a quantitative understanding of the above factors.

This study focussed on fuel temperatures at the following locations: pellet/disc interface; sheath/disc interface; and volume-average temperature in the pellet. In addition, this paper also describes a sensitivity analysis of some key factors that affect fuel temperatures; e.g., element linear power, element burnup, central hole size, and uncertainties in the values of heat transfer coefficients at the pellet/sheath, pellet/disc, and sheath/disc interfaces. A nomenclature is given at the end of the text (before the tables and figures).

THEORY

Figure 1 shows a schematic geometry of the UO_2 pellet, graphite disc and Zr-4 sheath for which temperature calculations were performed. It also shows the terms and definitions used in this paper. A two-dimensional finite element mesh, which represents the components of the geometrical system (pellet/sheath/graphite-disc), is shown in Figure 2. It allows for appropriate changes in the central hole dimensions. It contains 349 nodes connecting 534 finite elements, of which 13 are surface elements. To attain maximum accuracy, triangular finite elements were used and arranged in hexagonal patterns. The two-dimensional computer program FEAT [5] was used to calculate the temperatures. FEAT is based on solving the classical equation for steady-state non-linear conduction of heat. This computer program calculates temperature distribution in solids of arbitrary shapes. The code can model internal generation of heat, prescribed convection to heat sink, prescribed temperatures at boundaries, prescribed heat flux on surfaces, and temperature-dependent material properties, such as thermal conductivity. The calculations considered axisymmetric conditions, in that the temperatures were allowed to vary radially and axially along the pellet, sheath, and disc, but not around the circumference. Similarly, the geometry of the analyzed system and the boundary conditions were considered axisymmetric. Heat transfer at the interfaces (pellet/sheath, pellet/disc, and disc/sheath) was modeled through gap elements, where they were given associated surface area and heat transfer coefficients. Heat was transferred to the outside coolant via forced convection at surface elements on the outside of the sheath.

The mathematical modelling is based on the following assumptions:

1. Nuclear heat generation within the UO_2 pellet varies radially, and the axial variation of heat generation has been neglected.

2. No flow of heat is allowed from the pellet to the neighbouring pellets. Most of the heat flows from the pellet to the sheath, and from the pellet to the graphite disc to the sheath, and finally to the coolant. This is because of the large temperature difference between the coolant and fuel pellet. On the other hand, there is very little heat flow from one pellet to the other through the graphite disc, since neighbouring pellets are at similar temperatures.

3. The initial filling gas and the released fission gases are modeled as conducting finite elements. Heat flow via convection is included via appropriate heat transfer coefficients in the gaps.

4. The centre of the pellet is considered to have expanded thermally and filled the initial volume of the pellet dish.

CASE STUDY

The powers reported in this paper refer to *element* linear ratings, rather than *pellet* ratings. This means that for a given element rating, the pellets in graphite disc fuel operate at a higher volumetric heat generation rate, to compensate for heat *not* produced in the graphite. Similarly, the annular pellets operate at higher volumetric heat generation rate than the solid pellets. The latter effect is considered automatically in the FEAT code. The code's logic accounts for the variation of neutron flux across the pellet radius and through the central hole.

For the sensitivity analysis, a reference case was assembled based on a previous study [5]; it is listed in Table 1. The "base" value of power was 55 kW/m. The following ranges of parameters were assessed:

- element linear power: 35-75 kW/m,
- element burnup: 10-400 MWh/kg U,
- heat transfer coefficient at pellet/disc interface (Hpd): 1-15 $kW/m^2.K$,
- heat transfer coefficient at pellet/sheath interface (Hps): 7-16 $kW/m^2.K$,
- heat transfer coefficient at sheath/disc interface (Hsd): 0.5-10 $kW/m^2.K$, and
- central hole diameter: 0-3 mm.

The geometrical and the base data modelled are listed in Table 1. The thermal conductivity of the UO_2 pellet and Zircaloy cladding are from MATPRO-09 [6], and form a part of the FEAT code. The thermal conductivity of graphite was obtained from the manufacturer's product data sheet [7]. The radial distribution of the heat generation rate within the pellet was provided by the ELESTRES code. The heat transfer coefficient at the pellet/sheath interface (base value: 9 $kW/m^2.K$) was calculated using ELESTRES. The heat transfer coefficients at the pellet/disc (base value: 3.21 $kW/m^2.K$) and disc/sheath (base value: 9.64 $kW/m^2.K$) interfaces were scaled from previous heat transfer coefficients based on experimental measurements of corrosion rates in superheated steam.

RESULTS

The following fuel element temperatures were calculated using the FEAT code: pellet volume-averaged temperature (Tv); cross-section averaged temperature at the end plane of the pellet (Tcs); sheath temperature at the sheath/disc interface (Tsd); and maximum pellet temperature at the pellet/disc interface (Tpd). Results of the sensitivity analysis are shown in Figures 3 to 8. The impacts of introducing central holes of different sizes in lowering pellet temperatures were studied and quantified in Figures 9 through 12. Many computer simulations were performed to calculate the fuel temperatures for the following cases:

-the presence or absence of graphite discs, and
-four different diameters of the central hole.

Before we discuss the above results in detail, we first describe an assessment of the suitability of the FEAT code for this specific application. For this purpose, we reviewed the performance of fuel element NMT of experiment X-282 [1]. The fuel element contained graphite discs, and elliptical grain growth was observed in that irradiation; see Figure 13(a) [1]. This is typical of many graphite disc irradiations [1]. Grain growth depends mainly on time at local temperature, and accelerates rapidly above 1600°C. Hence the shape of the grain growth profile can be taken to be indicative of the shape of the local isotherm. Without the graphite discs, grain growth profiles normally do not show any significant gradient along the pellet length. Hence the elliptical grains in the graphite disc fuel reflect a pronounced heat removal via the graphite discs, resulting in elliptical isotherms.

Figure 13(b) shows typical isotherms calculated by the FEAT code. They are also elliptical. Thus the *shapes* of the calculated isotherms are very similar to the observed grain growth profiles. This provides a degree of confidence in the FEAT calculations.

Figure 13(b) also quantifies the benefit of graphite discs in reducing pellet temperatures. At the midplane of the pellet, the peak temperature is about 1950°C. At the endplane, graphite discs have reduced the peak temperature to about 1150°C. Thus, for this irradiation, the graphite discs reduced the local peak temperature by about 800°C.

DISCUSSION

Results of the sensitivity study are discussed in this section.

Effect of Element Linear Power

Figure 3 shows fuel temperature variations resulting from changes in element linear power. The data correspond to an annular pellet with a central hole diameter of 3 mm. As expected, pellet temperatures increase significantly with power. The figure shows that in this annular pellet, the maximum temperature at the pellet/disc interface stays below 1600°C at powers as high as 80 kW/m. The pellet volume-averaged temperature and the averaged cross-section temperature at the pellet end plane also increase as linear power increases. The sheath temperature at the sheath/disc interface increases linearly as the linear power increases, but it is well below 700°C, the temperature at which zirconium hydride is formed [1].

Effect of Burnup

Burnup affects the neutron flux depression across the fuel element, which in turn changes the temperature profile. As Figure 4 shows, the fuel temperatures at 55 kW/m are not too sensitive to this parameter. The effect of burnup on thermal conductivity of UO_2 was not accounted for in these calculations.

Effect of Heat Transfer Coefficient Between Pellet and Disc

Figure 5 shows that the pellet temperatures generally decrease as the pellet/disc heat transfer coefficient increases. The pellet temperatures become asymptotic at high values of the pellet/disc heat transfer coefficient. The sheath temperature is not affected much by the increase in the pellet/disc heat transfer coefficient.

Effect of Heat Transfer Coefficient Between Pellet and Sheath

Figure 6 shows the variation of fuel temperatures with the pellet/sheath heat transfer coefficient. The pellet temperatures decrease as the pellet/sheath heat transfer coefficient increases, and eventually reach an asymptotic value. The sheath temperature decreases slowly with the pellet/sheath heat transfer coefficient. It tends to be relatively constant, which means that it is not sensitive to changes in the pellet/sheath heat transfer coefficient.

Effect of Heat Transfer Coefficient Between Sheath and Disc

As Figure 7 shows, pellet temperatures decrease as the sheath/disc heat transfer coefficient increases. As the sheath/disc heat transfer coefficient becomes very large, the pellet temperatures become constant. The sheath temperature increases as the sheath/disc heat transfer coefficient increases, due to the increase in heat flow from the pellet through the graphite disc to the sheath. This increase in heat flow causes a local increase in sheath temperature at the sheath/disc interface.

Effect of Central Hole Size

As Figures 8-12 show, the maximum pellet/disc interface temperature is decreased by about 200°C as the central hole diameter increases from 0 to 3 mm, while the other fuel temperatures have no significant changes in their values as the central hole diameter increases.

In summary, the sensitivity study shows the following trends:

1. Element linear power has a strong effect on the fuel temperatures, in that the pellet temperatures increase considerably as the linear power increases.

2. Figure 11 shows that changing the hole diameter from 0 to 3 mm reduces the maximum pellet temperature at the pellet/disc interface by about 200°C at 55 kW/m, which is equivalent to a reduction of about 12 kW/m in element power.

3. From Figure 9, it is clear that bulk fuel temperatures are not affected much by the central hole. The sheath temperature at the disc interface is also not changed much by the hole.

   Central holes displace the source of nuclear heat closer to the heat sink (coolant), which reduces the temperature in the inner regions of the pellet. On the other hand, increasing the hole diameter means that less uranium is utilized to produce the same power, which leads to increasing the pellet average temperature and the end-temperature. The result of these two counteracting effects is no significant net change in the pellet average temperature.

   For these reasons, fission gas release and total expansion are expected to be similar in both annular and solid pellets. But their impacts on sheath stresses may be significantly different. In solid pellets, all the pellet expansion goes to the outer surface of the pellet and is transmitted to the sheath. An annular pellet may have the same total expansion, but some of it will likely go towards the hole, leaving less expansion at the outer surface. This will likely lower sheath stresses. An example of this is given in Figure 13(a), which shows the post-irradiation profile of a pellet that was initially annular. Irradiation "filled" the initial hole substantially, which illustrates the tendency of the annular pellet to expand inwards.

4. Pellet temperatures (Tv, Tcs, and Tpd) decrease asymptotically as the heat transfer coefficients (Hpd, Hps, and Hsd) increase. The sheath temperature at the disc interface (Tsd) increases as the disc's heat transfer coefficients increase, while it decreases as the pellet/sheath heat transfer coefficient increases. This is because increasing the disc's heat transfer coefficients provides an easy path for the heat to flow from the pellet to the sheath via the graphite disc. Consequently, the temperature of the sheath (Tsd) increases locally. Also, increasing the pellet-to-sheath heat transfer coefficient increases the heat flux from the pellet to the sheath, which decreases the sheath temperature over the graphite disc.

CONCLUSIONS

1. Graphite discs reduce the local peak temperature significantly. For example, in irradiation X-282, the peak temperature near the graphite discs was about 800°C lower than the corresponding temperature away from the discs.

2. Isotherms calculated by the FEAT code have elliptical shapes, which are very similar to the grain-growth profiles observed previously in irradiated graphite-disc fuel.

3. A hole of 3 mm diameter lowers the maximum pellet/graphite-disc interface temperature by about 200°C (at an operating power of about 55 kW/m).

4. The sheath temperature at the sheath/graphite-disc interface is always below the limiting temperature of 700°C, at which zirconium hydride is formed.

5. Overall, central holes do not have a major impact on the bulk temperature of the pellet. However, in an annular pellet, some of the pellet expansion will be accommodated in the central hole, leaving less expansion at the outer surface. This will likely lower sheath stresses.

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NOMENCLATURE

H_{pd}: Heat Transfer Coefficient at the Pellet/Disc Interface

H_{ps}: Heat Transfer Coefficient at the Pellet/Sheath Interface

H_{sd}: Heat Transfer Coefficient at the Sheath/Disc Interface

T_{cs}: Cross-section Average Temperature at the End Plane of the Pellet

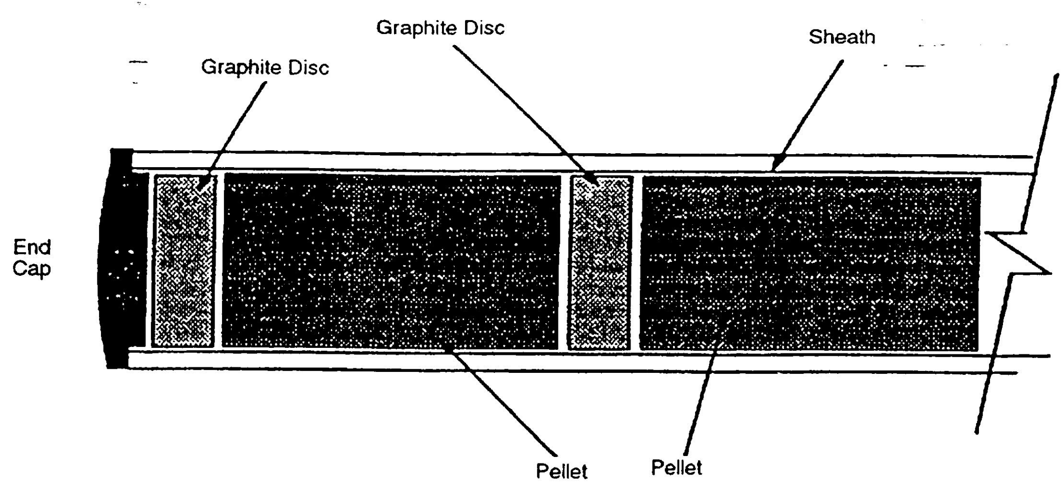
T_{pd}: Maximum Temperature in the Pellet at the Pellet/Disc Interface

T_{sd}: Sheath Temperature at the Sheath/Disc Interface

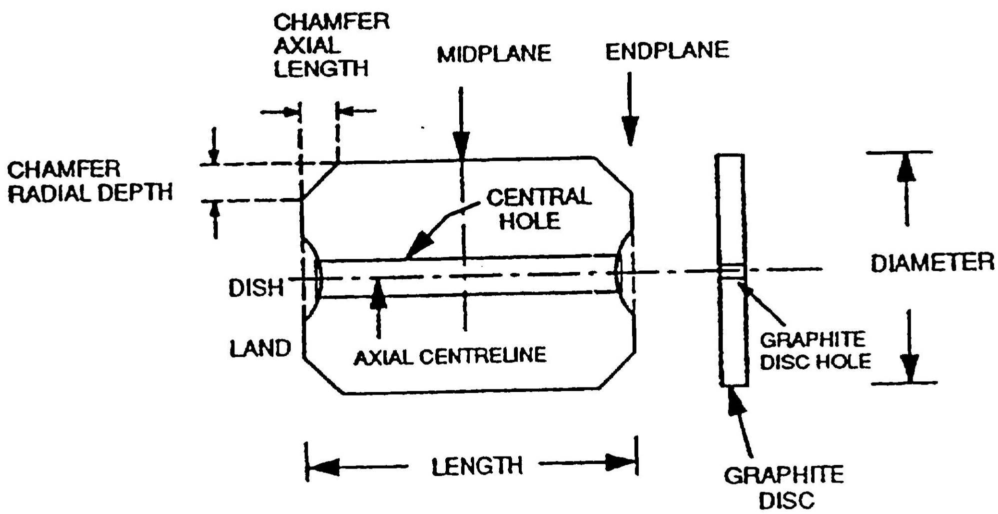
T_v: Volume-Average Temperature in the Pellet

Table 1: Base Case Data

Geometry	
- Ratio of pellet length to diameter	0.705
- Ratio of pellet hole to diameter	0.25
Material Conductivity (W/m.K)	
- UO_2 and Zircaloy	as per MATPRO-09, 11
- Graphite Disc	120 at 20°C
	65 at 500°C
	50 at 1000°C
- Air	0.002
Heat Transfer Coefficients (kW/m^{2}K)	
- Pellet/sheath	9.0 from ELESTRES code
- Sheath/coolant	50.0 from ELESTRES code
- Pellet/disc	3.21
- Disc/sheath	9.64
Base Data	
- Element Linear Power (kW/m)	55
- Burnup (MWh/kg.U)	200
- Enrichment (U235 weight percentage)	1.4



(a) Fuel Element



(b) Pellet and Graphite Disc

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Figure 1 Definitions of Terms

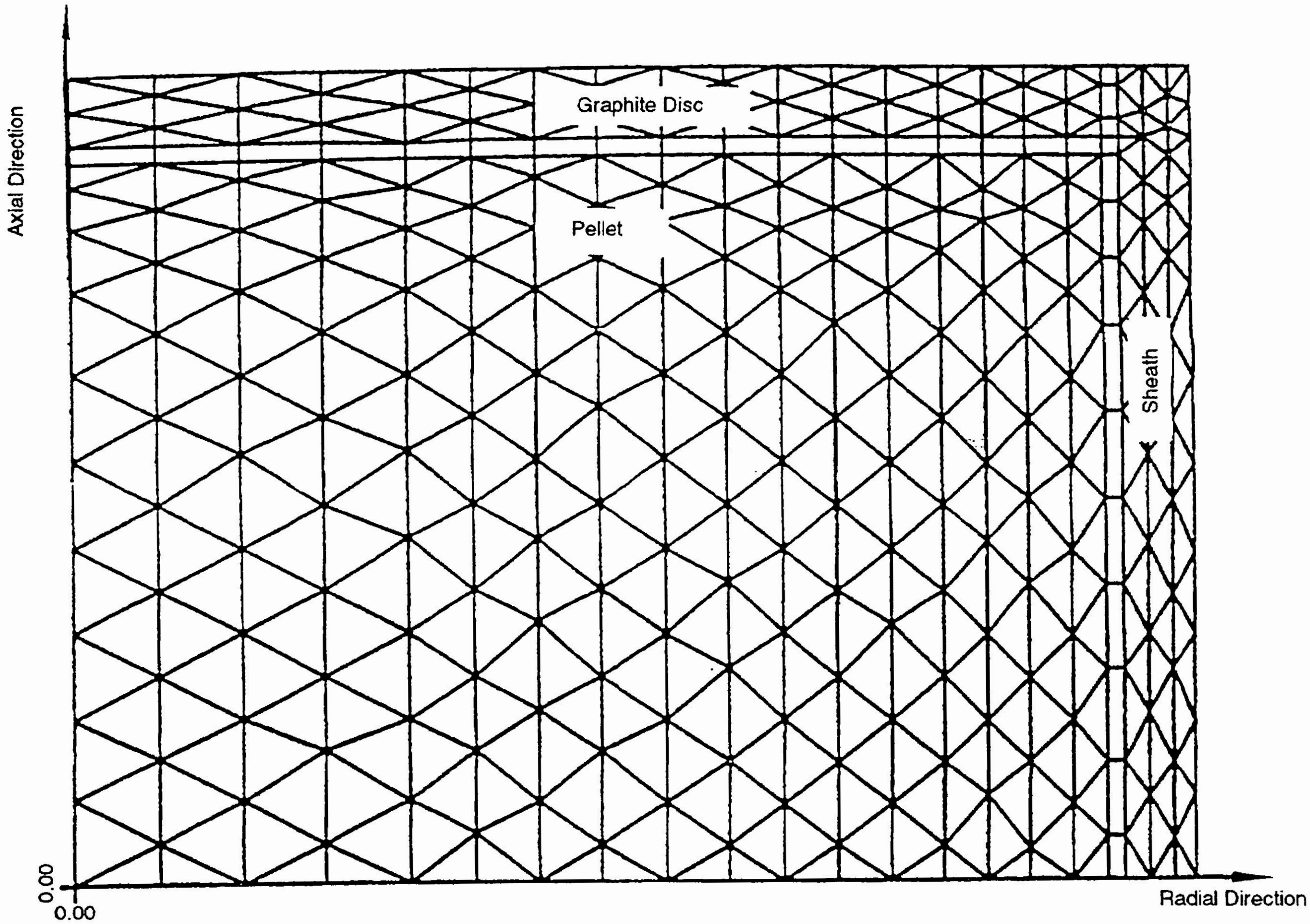

Figure 2 Finite Element Mesh of the Model

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Legend
× Tpd: Maximum Temperature in the Pellet at the Pellet/Disc Interface
△ Tv: Volume-Average Pellet Temperature
□ Tsc: Cross-Section Average Temperature at the End Plane of the Pellet
○ Tsd: Sheath Temperature at the Sheath/Disc Interface

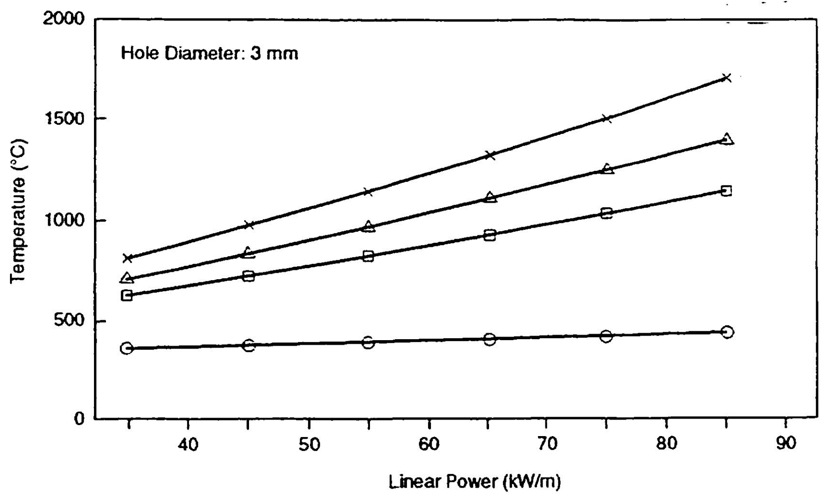

Figure 3 Fuel Temperatures vs Linear Power

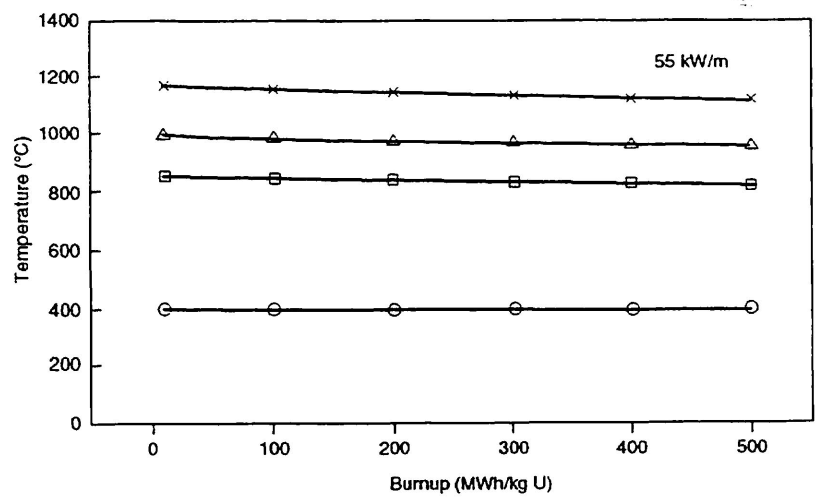

Figure 4 Fuel Temperatures vs Element Burnup

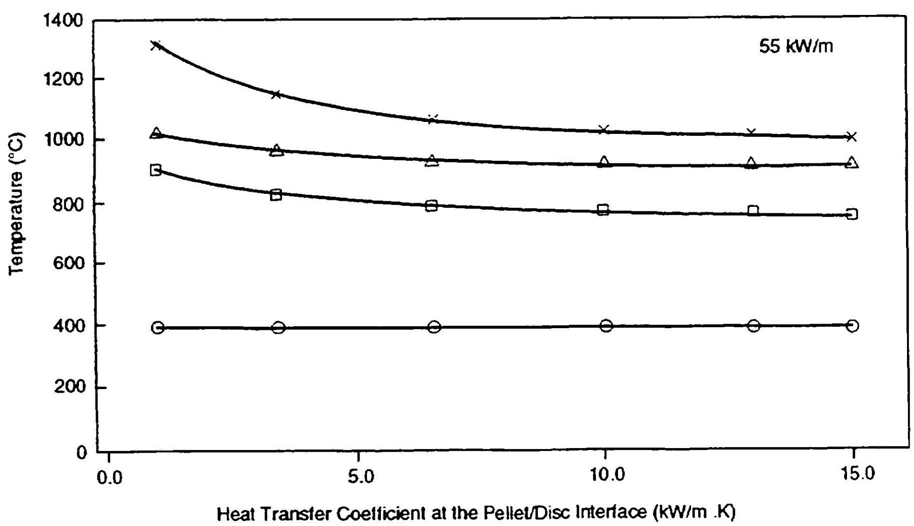

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Figure 5 Fuel Temperatures vs Pellet/Disc Heat Transfer

Legend
× Tpd: Maximum Temperature in the Pellet at the Pellet/Disc Interface
△ Tv: Volume-Average Pellet Temperature
□ Tsc: Cross-Section Average Temperature at the End Plane of the Pellet
○ Tsd: Sheath Temperature at the Sheath/Disc Interface

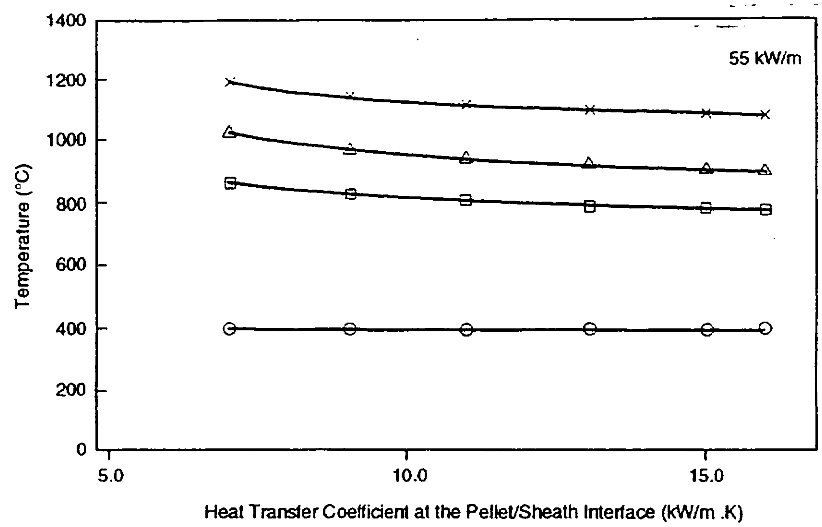

Figure 6 Fuel Temperatures vs Pellet/Sheath Heat Transfer

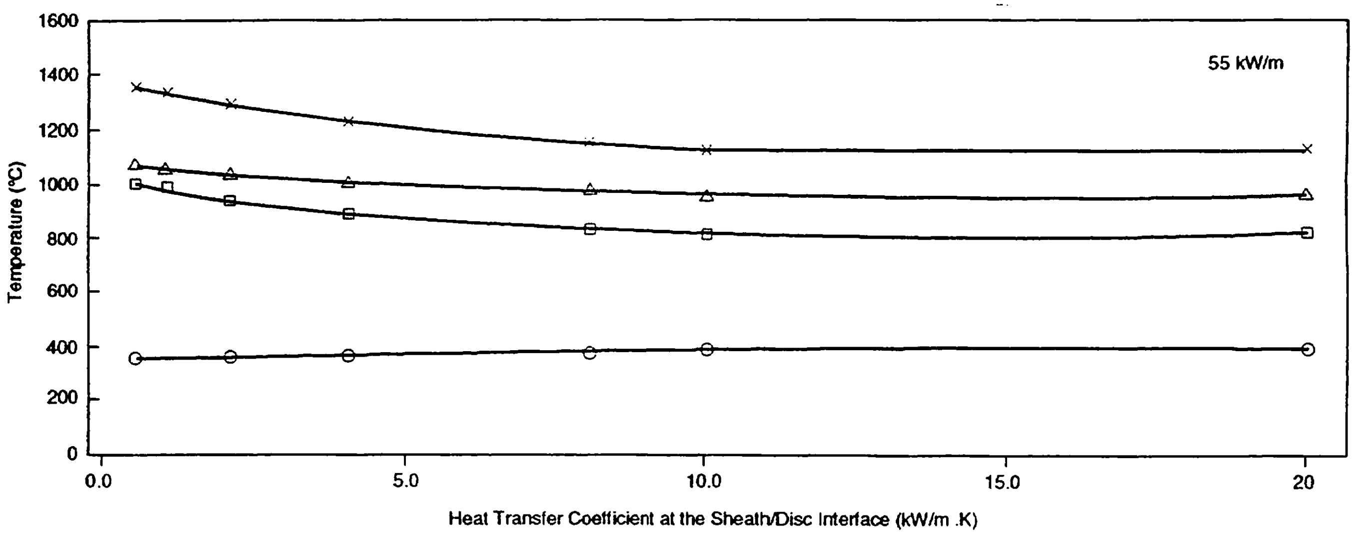

Figure 7 Fuel Temperatures vs Sheath/Disc Heat Transfer

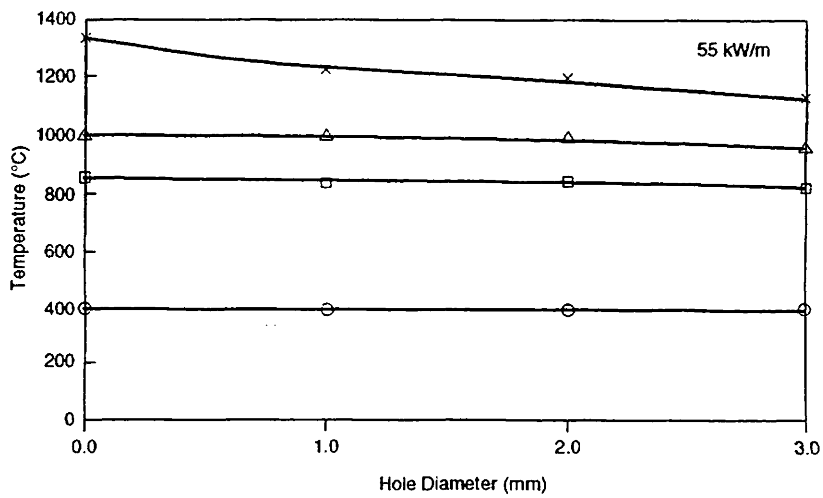

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Figure 8 Fuel Temperatures vs Central Hole Diameter

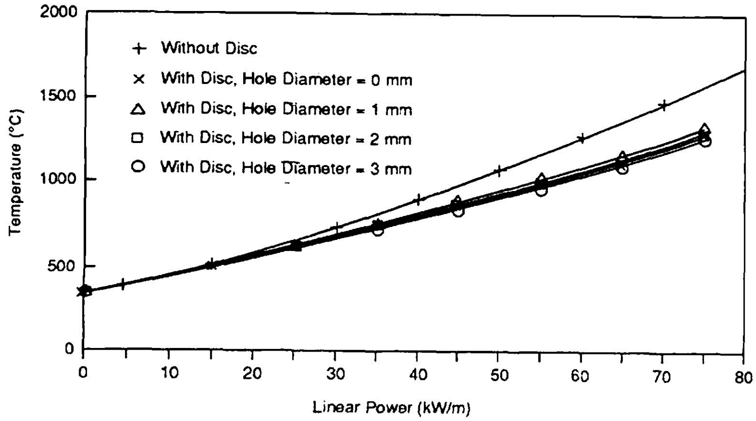

Figure 9 Volume-Average Temperature in the Pellet, Tv

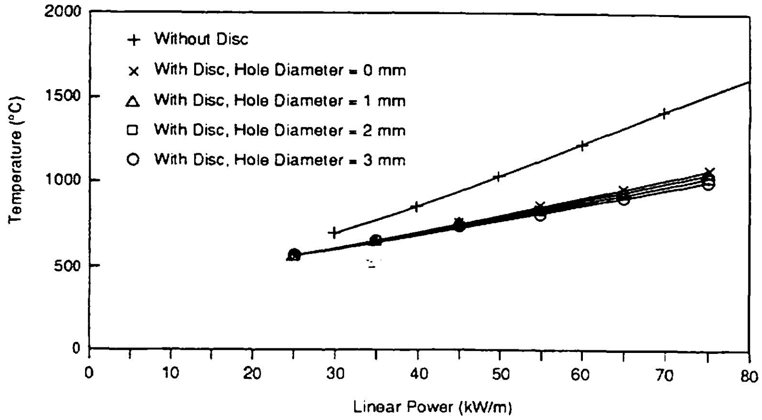

Figure 10 Cross-Section Average Temperature at the End Plane of the Pellet, Tcs

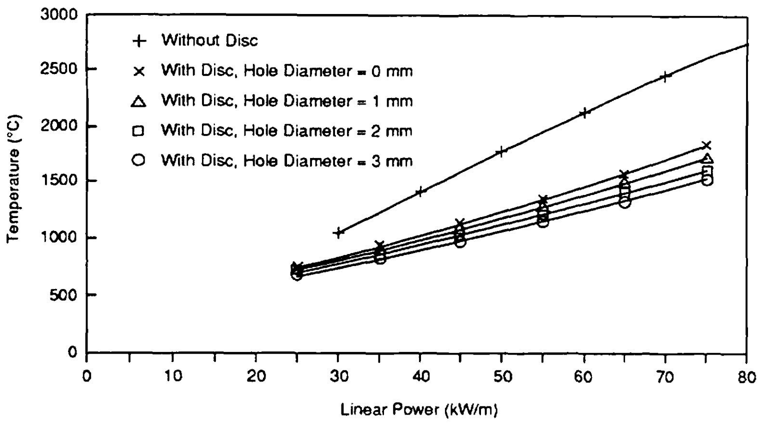

Figure 11 Maximum Temperature in the Pellet at the Pellet/Disc Interface, Tpd

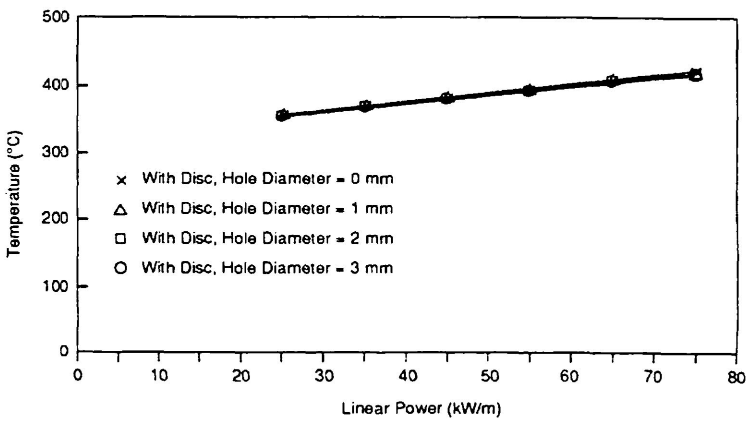

Figure 12 Sheath Temperature at Disc Interface, Tsd

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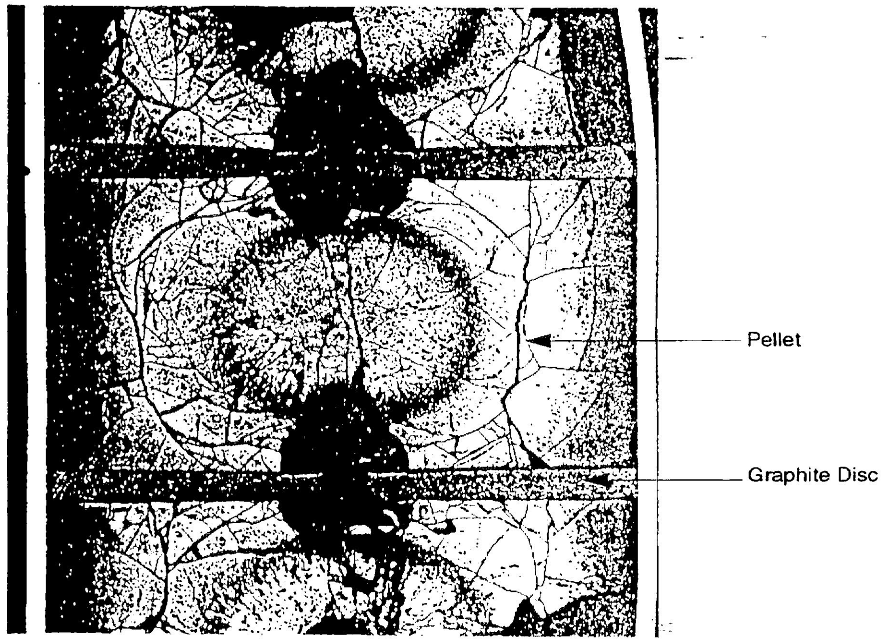
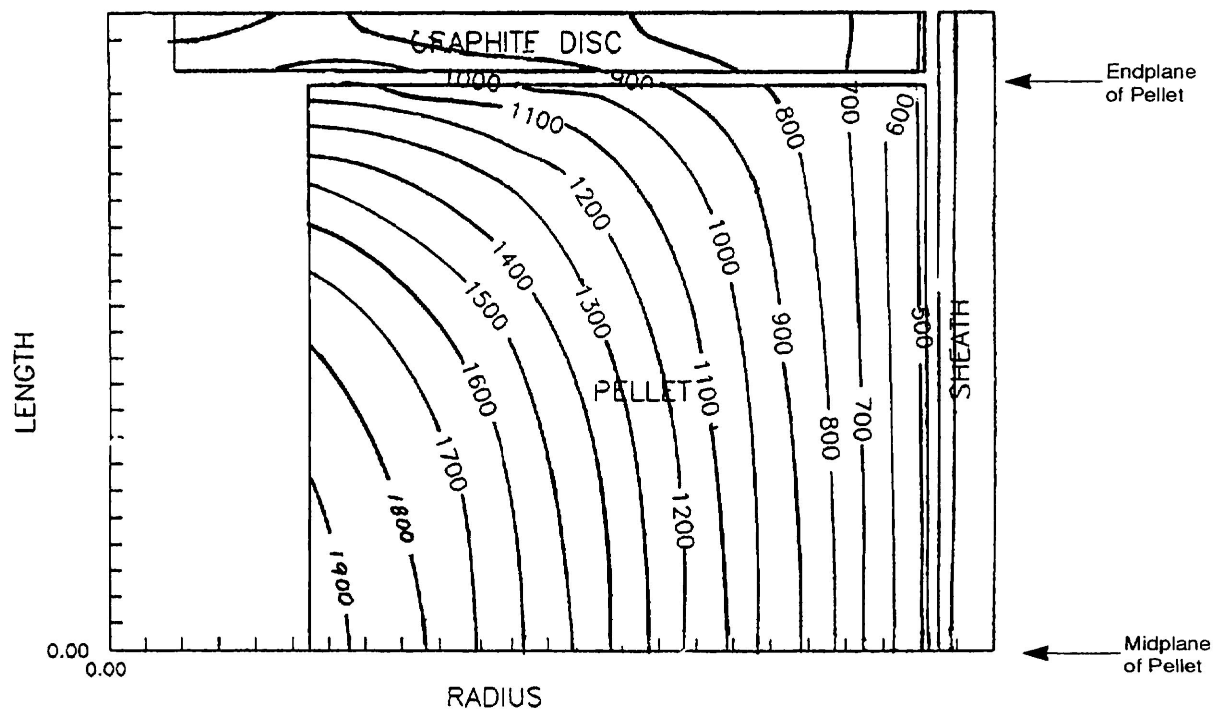


(a) Elliptical grain growth observed in irradiation X-282 (Reference 1)



(b) Elliptical isotherms calculated by FEAT (°C)

Figure 13 Shapes of Grain Growth and Isotherms

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