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ABSTRACT

In normal reactor operation, oxide fuel pellets will crack. The majority of the pellet segments will lie against the cladding. When temperature in the central region of the fuel during irradiation is raised to the plastic region, crack healing occurs. The repetition of cracking-healing-cracking sequence resulting from repeated power cycle has a significant effect on fuel relocation. The fuel pellet relocation must be known since it effects the cladding life time. ~~This work~~ describes the fuel pellet cracking and healing phenomena in reactor operation and ~~also discusses~~ the pertinent method of analysis.

INTRODUCTION

In normal reactor operation, oxide fuel pellets undergo irreversible structural changes under irradiation.

The fuel relocation is the most complex machanism in the pin and, therefore, the most difficult problem in fuel modeling. It is the result of densidication, thermal expansion, radial cracking of oxide resulting from the differentital thermal expansion, fuel swelling due to solid and gaseous fission products, fuel restructuring, crack healing due to the above mechanisms, etc. All these mechanisms are interconnencted. Such mechanisms are representative only for very special cases: fuel power, power cycling, initial gap size, power history, fuel density, fuel stability, etc. No generalized phenomenological relationships can be deduced.

Pellet cracking and fuel desification are competing gap closure mechanisms. The pellet cracking thends to decrease the as fabricated pellet-to-cladding gap, the fuel densification tends to increase it. These two mechanisms are usually completed after a few hundred hours of irradiation. Fuel pellet swelling and clad creep down generally affect the gap size after a significant period of irradiation (4,000 to 10,000 hours), and results in additional gap closure from that previously attained from pellet cracking.

The fuel pellet relocation must be known since it affects the cladding lifetime. The expansion of the pellet imposes a severe fatique load on the cladding. Cracked pellets may lead to local forces on the cladding. Once it becomes plastically unstable, fracture may occur due to the concentration of strain.

Recent studies show that pellet cracking and healing play an important role in fuel relocation, thus resulting in substantial closure of the initial as fabricated pellet-to-cladding gap. The gap conductance is strongly increased[15]. The presence of cracks facilitates the escape of gaseous fission products into the gap, so that the gap conductivity will change with irradiation history[2]. MacDonald[14] reports that Storer et al. concluded on the basis of their experiments that the cracking of the UO_2 pellets will effectively reduce its thermal conductivity.

We see that pellet cracking affects the fuel rod in a number of ways. The treatment of pellet cracking in fuel modeling codes is still on a rather tenuous basis.

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The intent of this work is to provide an introduction to the fuel pellet cracking phenomena during reactor operation.

2 – PLASTIC BEHAVIOR OF UO_2

As most ceramics, UO_2 is a brittle material at temperatures less than about one-half the melting point ($\sim$ 1300°C) and in absence of radiation. At higher temperatures UO_2 becomes ductile.

The deformation properties of stoichiometric UO_2 have been invetigated as a function of temperature[19,21]. Typical results are shwn in Figure 2.1 in which three regions of temperature can be defined: (1) Brittle region (25°C to 1200°C) – this region is completely brittle. At 1200°C, which is defined as brittle-to-ductile transition temperature, plastic deformation first occurs. At higher strain rates than the rate at which the rate in Figure 2.1 was obtained, the transition from brittle-to ductible behavior occurs at higher temperatures; (2) Semi-brittle region (1200°C to $\sim$ 1400°C) – this region represents the transition from completely brittle to purely ductile behavior. In this region measurable plastic strain occurs before rupture, but the ultimate tensile strength of material still remains high; (3) Plastic region ($T > \sim$ 1400°C) – in this region the material is completely ductile. The ultimate strength decreases rapidly with temperature, and appreciable plastic deformation occurs before ductile fracture.

Figure 2.2 shows a simple cracking model of a fuel pellet under irradiation. The center region of the pellet where $T > \sim$ 1400°C is considered to be completely ductile, flows easily under low stresses and possesses no strength, therefore is not cracked. The outer region where $T <$ 1200°C is regarded as completely brittle and is believed to be cracked by thermal stresses set up by the temperature gradient in the fuel. The narrow central region which is strong and moderately ductile, is called bridging annulus. Gittus, Howl and Hughes[6] have used this simple mechanical model of UO_2 to calculate the stress and strain distributions developed in a fuel pin during irradiation.

3 – FUEL PELLET CRACKING

In the very early stage of in-pile life, the non-uniform thermal expansion of the fuel within the pellet results in pellet cracking, due to the bad tensile strength of the ceramic oxide.

Since the temperatures near the center of the pellet are higher, the center has a tendency to expand more than the periphery, thus inducing tensile hoop stress near periphery of the pellet and compressive hoop stress near the center. When subjected to purely compressive loads, ceramics such as UO_2 are found to be far stronger than they are in tension. The compressive strength of UO_2, for exemple, is nearly an order of magnitude greater than the ultimate tensile strength[17,19]. Since the pellet cannot sustain much tensile stress, that is, approximate 1.5×10^5 KN/m^2[21], radial cracks will be initiated at the periphery of the pellet. These cracks will propagate inward until the hoop stress drops below the crack propagation stress of the material at the local temperature, provided this temperature is below the brittle-to-ductile transition temperature.

At the beginning of reactor operation, the fuel is in absence of swelling or creep strain. The fuel cracking phenomena may be treated by thermoelastic theory.

Consider an infinitely long cylindrical fuel pin of radius R. Assume that the thermal conductivity is independent of temperature. The temperature difference from the center line of the fuel to the surface is given by.

$$T_o - T_s = \frac{q'}{4\pi \bar{K}}$$

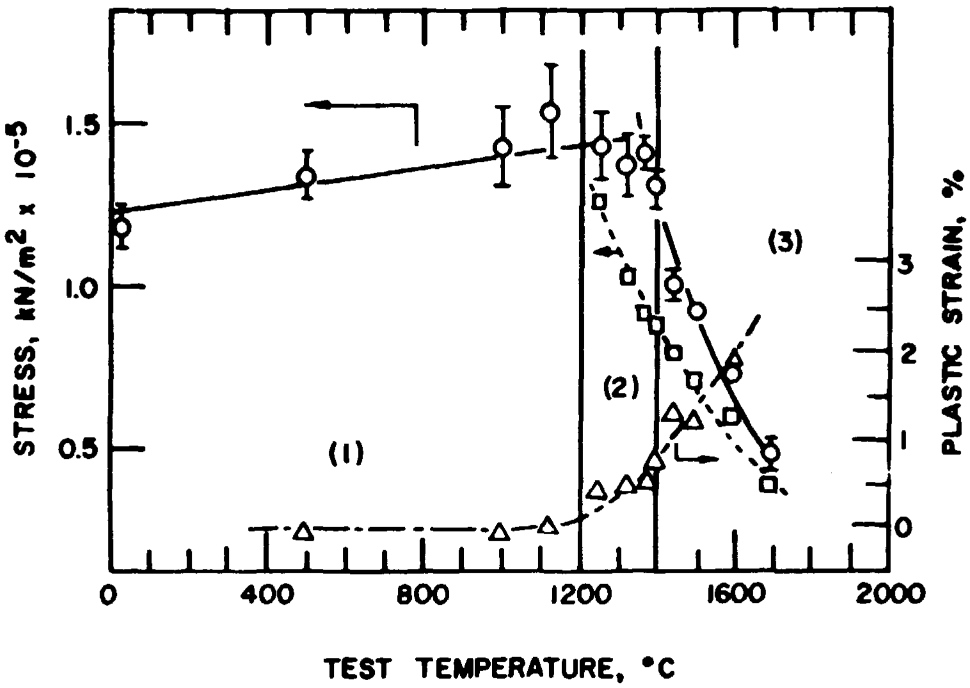

Figure 2.1 – Fracture and Flow Characteristics of UO_2 as a Function of Temperature. -o, Ultimate Tensile Stress . . . □, Elastic Limit .–.–△, Total Plastic Strain. The Strain Rate was 0.1 hr^{-1} [3].

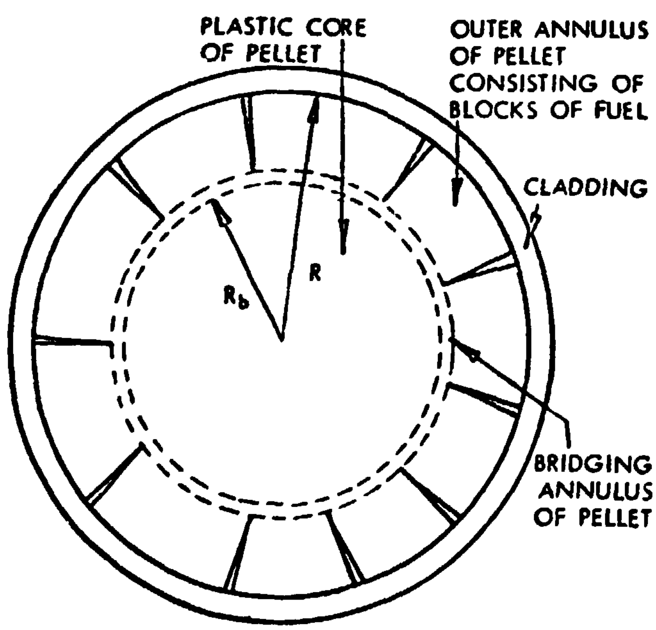

Figure 2.2 – Model Used for Crack Distribution in Fuel Pellet. R = Pellet Radius; R_b = Radius of Bridging Annulus[4].

where

q' = linear power

$\bar{K}$ = average thermal conductivity of the fuel

Application of thermoelastic theory of this situation shows that the tangential or hoop stress in the fuel, σ_θ, varies with fractional radius according to[19]:

$$\sigma_\theta = - \frac{\alpha \; E \; q'}{16\pi(1-\nu)\bar{K}} [\, 1 - 3 \; (\frac{r}{R})^2 \,] \tag{3.2}$$

where

α = linear coefficient of thermal expansion

E = Young's Modulus

ν = Poisson's Ratio

Stresses are positive if in tension. The above equations indicate compression of the fuel out to a fractional radius of $(1/3)^{1/2}$ and tensile hoop stress thereafter. The maximum stress, which occurs at the outer surface of the fuel, is given by:

$$(\sigma_\theta)_{max} = \frac{\alpha \; E \; q'}{8\pi(1-\nu)\bar{K}} \tag{3.3}$$

The typical values of UO_2 properties are the following:

$\alpha = 10^{-5}\ ^\circ C^{-1}$

$E = 1.4 \times 10^8 KN/m^2$

$\nu = 0.3$

$\bar{K} = 0.028\ W/cm^\circ C$

Application of Eq. (3.2) shows that the fracture stress of UO_2 ($\sim 1.5 \times 10^5 KN/m^2$) is attained at the outer region of the fuel pin when the linear power is $\sim$ 50 W/cm. Since this value is an order of magnitude lower than the normal linear power of an operating fuel pin, it is evident that cracking of the brittle outer region of the fuel is unavoidable.

From Eq. (3.1), a temperature difference of $\sim 150^\circ C$ is sufficient to produce a thermal stress to crack the pellet. Temperature differences as low as $60^\circ C$ have been reported to be sufficient to cause cracking in UO_2 fuel [5].

4 – FUEL PELLET HEALING

When temperature in the central region of the fuel during irradiation is raised to the plastic region, crack healings occur. The cracks heal progressively outward from the center.

At temperature range of 1400 to 1700°C, which is the equiaxed grain growth region, cracked portions of pellet sinter together as a result of volume and surface diffusion mechanisms[19]. At fuel temperatures above 1700°C, cracks heal by vapor transport phenomena[19]. So these phenomena proceed not only in the bulk material resulting in densification and central hole formation, but also inside the cracks. The cracks induce a nucleation effect regarding the columnar grain growth. They can be considered as loci of grain nucleation in the hot zone of the pin. Figure 4.1 shows the macrograph of an FBR pin (500 W/cm)[9]. In the zone where columnar grains grow, all radial cracks have been healed.

As crack healing is governed by diffusion, it is a time-temperature dependent process. Since the extent of crack healing influences not only in fuel relocation, but also swelling and gas release behavior in the life of the fuel element, it is important to establish the kinetics of the process which has not yet been studied in detail up-to-date.

Roberts and Wrona[20] performed experiments to predict the healing of initial start-up cracks in UO_2 pellets, before the fuel comes into contact with the cladding. Results indicate that healign occurs at the same rate as grain growth. Figure 4.2 shows the recovery of room temperature fracture strength in UO_2 as a function of crack healing time and temperature. The figure indicates that the as fabricated strength is fully recovered after $\gtrsim$3, 11 and 48 hours at 2000°C, 1800°C, and 1600°C, respectively. The following empirical correlation is established:

$$(\sigma/\sigma_F)^2 = (\sigma_o/\sigma_F)^2 + (6.5 \times 10^{10}/\sigma_F{}^2)\, t\, \exp(-55000/RT) \qquad (4.1)$$

where

σ_o = as-shocked strength

$t < t_f$ with $\sigma = \sigma_F$ at $t = t_f$

This equation is represented by the dashed lines in Figure 4.2.

Experiments of measurements of crack sintering rates in UO_2 pellets have also been performed by Ainscough and Rigby[1]. They believe that crack healings occur provided the pellet is under compression, and that healing takes place in two stages: crack closure followed by sintering. The rate of closure under irradiation is governed by the local creep and swelling characteristics of the fuel and is believed to be the faster of the two processes. So the rate determining step in crack healing should be the rate at which the two faces of a crack, in contact with each other, sinter together. They established an empirical rate equation for crack healing:

$$t = 1.8 \times 10^{-6} \exp(32000/T)/P$$

where

t = time for complete healing (hours)

T = temperature (°K)

P = pressure acting at the position of the crack surfaces in contact (MW/m^2)

Figure 4.3 shows the crack healing time as a function of temperature for P = 1 MN/m^2, which is believed to be approximately the average interface pressure during crack healing. The actual interface pressure acting across a crack is a complex function of the external restraint on the fuel and of its densification and swelling rates.

Lovejoy and Evans[13] proposed another crack healing model based on first principles that

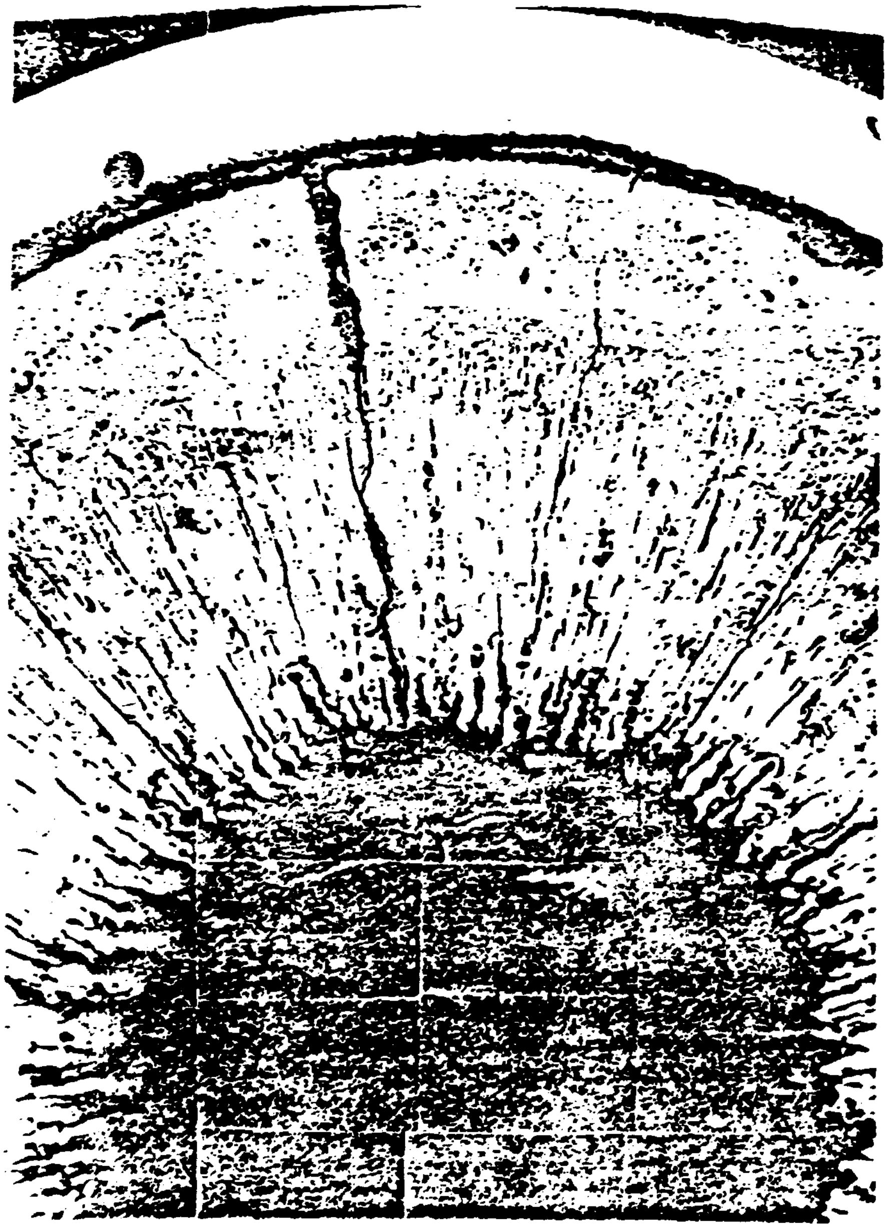

Figure 4.1 – Macrograph of a Typical FBR Pellet, Showing the Fuel Structural Zone with Cracks Healing in the Columnar Grain Zone[6].

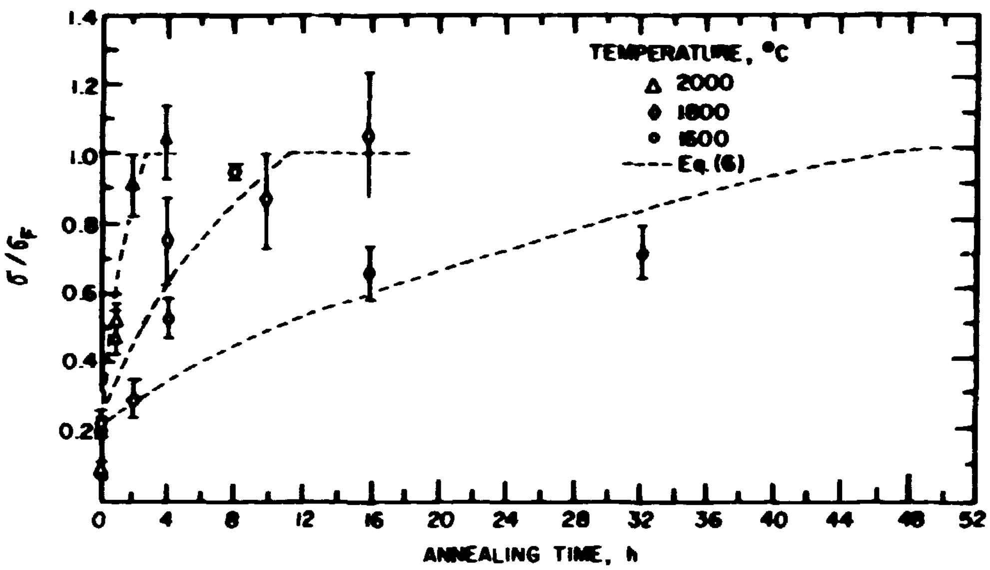

Figure 4.2 – Recovery of Room Temperature Strength in UO_2 as a Function of Crack Healing Time and Temperature[1].

predicts the recovery of fracture strength in LMFBR fuel as a function of time, temperature and stress. The relation fits the data well. Data published by previous authors[20,1] were used to calculate the values for the correlation constants. The ratio $\sigma_f(t)$ over σ_F is given by:

$$\frac{\sigma_f(t)}{\sigma_F} = \frac{\sigma_o}{\sigma_F}\left[1 + \frac{1.3\text{x}10^{10}\ \exp(-55000/RT)t \times (1 - 4.26\text{x}10^{-3}\ \bar{\sigma})}{T}\right]^{1/3} \tag{4.3}$$

where

σ_F = uncracked fracture strength

t = time (hours)

T = temperature (°K)

R = 1.987

$\bar{\sigma}$ = pressure normal to crack face (psi)
($\bar{\sigma} < 0$ – compressive stress)

Figure 4.4 shows the time required for complete crack healing vs. inverse temperature for several stress states in the fuel.

Large fuel-to-cladding gap experiments[9] show that external mechanical loads are not necessary to heal cracks; thermal effects are sufficient for this.

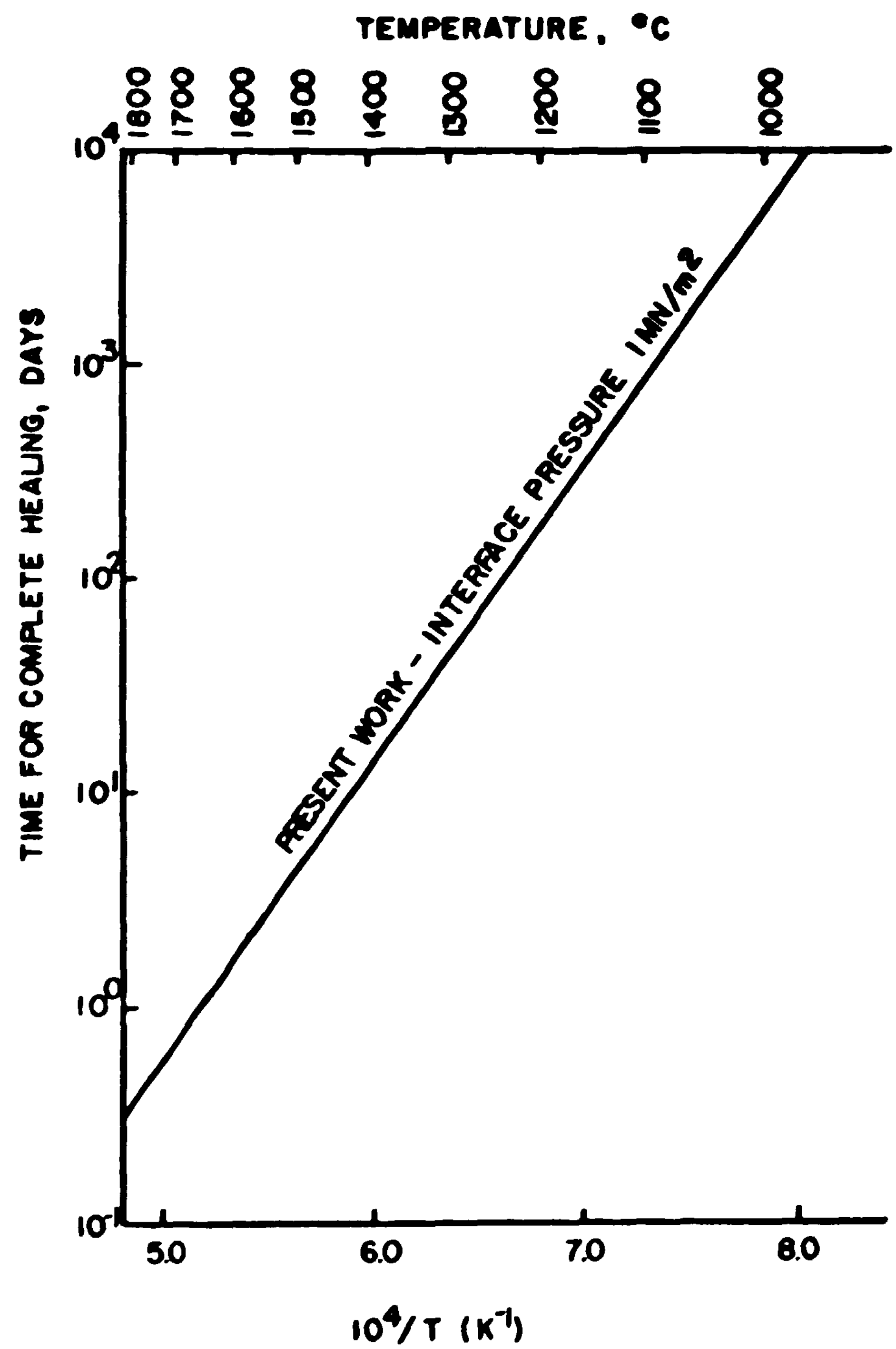

Figure 4.3 – Crack Healing Time as a Function of Temperature[2].

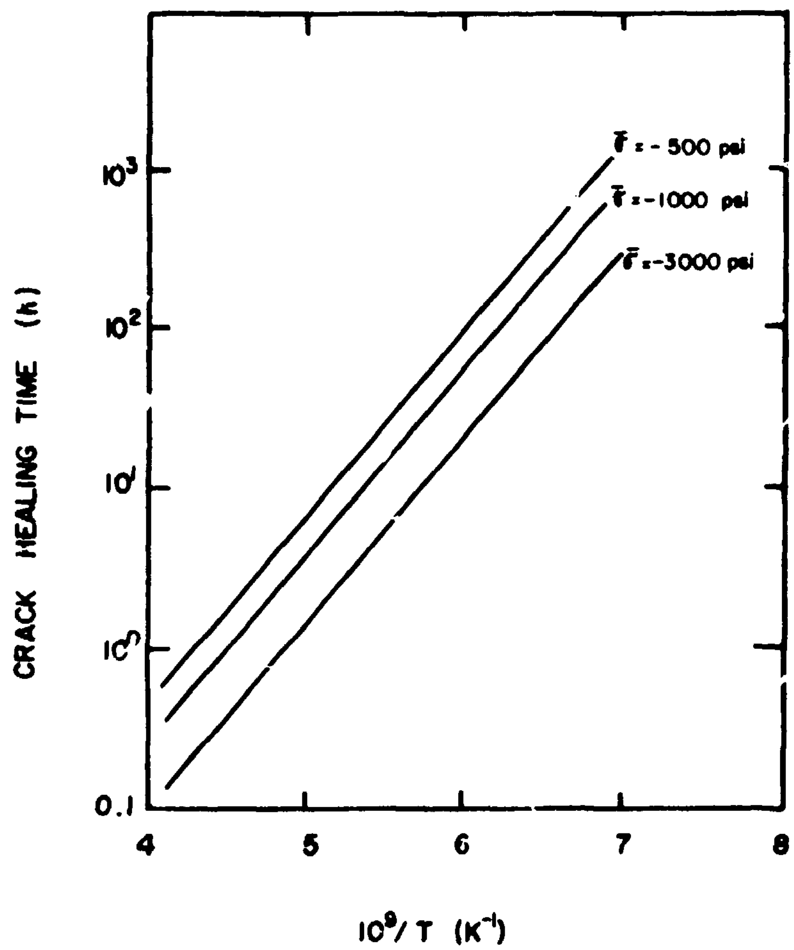

Figure 4.4 – Crack Healing Time as a Function of Inverse Temperature for Several Stress States[2].

5 – EFFECT OF PELLET CRACKING AND HEALING ON GAP CLOSURE

In the event of a reduction in power, the temperature near the center of the pellet drops much more than the temperature near the periphery. Since the center material tends to contract more than of the pellet. The reduction in power is a relatively short process. The tensil stress set up by the contracting pellet is not relieved by creep processes, but causes formation of radial and circumferential cracks. This time the radial cracks open from the center.

During the next heating up phase, cracks are again healed outward from the center.

This repetition of cracking-healing-cracking sequence resulting from repeated power cycle has a significant effect on fuel relocation. This sequence accelerates gap closure as a result of a radial ratcheting mechanism.

An approximate calculation of tangential or creep strain, $\Delta R/R$, is given below[18]:

Suppose the radial cracks extend from the periphery of the fuel to the radial position R_c. The hoop strain of the solid portion of the fuel pin between the center and R_c is:

$$\frac{\Delta R_c}{R_c} = \alpha \left(\frac{T_o + T_c}{2}\right)$$

where

T_o = central temperature

T_c = temperature at the root of the crack

α = linear coefficient of expansion

The width of the outer cracked portion is: $L_c = R - R_c$. The approximate strain of these blocks of solid is:

$$\frac{\Delta L_c}{L_c} = \alpha \left(\frac{T_c + T_s}{2}\right)$$

where

T_s = surface temperature of the fuel.

The total radial displacement is

$$\Delta R = \Delta R_c + \Delta L_c = 1/2\ \alpha R \left[\left(\frac{R_c}{R}\right)T_o + T_c + \left(\frac{R-R_c}{R}\right)T_s\right] \qquad (5.1)$$

For a parabolic temperature distribution

$$T_c = T_o = (T_o - T_s)\ \left(\frac{R_c}{R}\right)^2$$

Thus

$$\frac{\Delta R}{R} = ½\ \alpha\ (1 - \mu_c - \mu_c^2)T_o + (1 - \mu_c + \mu_c^2)T_s \qquad (5.2)$$

where

$\mu_c = R_c/R$ = fractional radius at which the cracks begin.

For $T_o = 2500 - 300 = 2200°K$, $T_s = 1000 - 300 = 700°K$, and $\alpha = 1 \times 10^{-5}\ °K^{-1}$:

$\left(\frac{\Delta R}{R}\right)_{\text{uncracked}} = 0.0145 \qquad \mu = 1$

$\left(\frac{\Delta R}{R}\right)_{\text{cracked}} = 0.0163 \qquad \mu = (1/3)^{1/2} \qquad$ (from Eq. 3.2)

This difference in the hoop strain is due to the inability of the cracked outer region to contain the expansion of the hot fuel in the interior of the pellet[18].

During the cooling down phase, the fuel does not contract to the center because of two reasons: 1) the bridging annulus has suffered a measurable plastic strain when the fuel first goes on to power; 2) formation of central cracks.

During the next heating up phase, the fuel cracks again to a more external location: the gap is smaller before cycling[4].

Healing of cracks in the columnar zone transfers the cracked area to the central hole. Healing of a circumferential crack takes up the gap clearance equalling the width of the crack, while filling in a radial crack of width f_r, takes up $S_r = f_r/2\pi$[22].

Thus power cycling causes an increase in apparent volume of the fuel by the development and healing of internal cracks.

Although somewhat arbitrary, only power cycles in which a power variation in excess of 50 percent occurred were considered significant to gap closure[8].

If cyclings are performed at central temperatures lower than 2000°C at start of life, the cyclins have no effect on gap closure[9]. Comparision between calculations with and without power cycling[8] shows that good agreement with experiments can only be obtained by considering cycling after some 5 – 10 days of irradiation and ignoring it before. If cyclings are performed at higher temperatures, they induce a faster gap closure. When the cycling is delayed, its effects increase.

An experiment was performed by Lawrence[12] to determine the effects of power cycling on the fuel-to-cladding width in LMFBRs. Results of irradiations show an average 40% decrease in the gap after zero-to-full power cycle during 100 h, and a 65% decrease after five 20 h cycles. Both experiments were performed with the same rate of power increase during charging (60%/h) and rate of power decrease during discharging (3%/sec). Heat ratings were between 24 and 26 kW/ft and the initial gap width was 0.011 in.

Figure 5.1 shows the number of efficient cycles to mechanically take up fuel-to-cladding gap[22]. The initial gap width was 0.012 in.

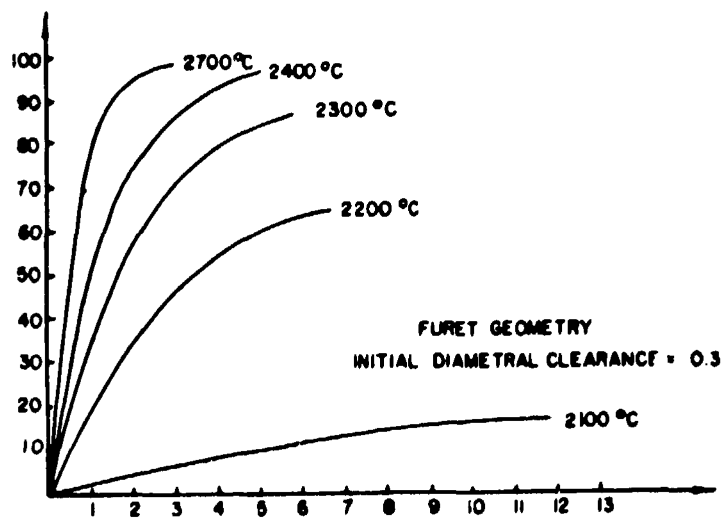

Figure 5.1 – Number of Efficient Power Cycles to Mechanically Take Up Fuel-to-Cladding Gap[7].

The rate of gap closure due to pellet cracks in controlled by the number of cyclings, the cycling period, and the temperature profile inside the fuel.

6 – PELLET CRACKING ANALYSIS IN LIFE-II COMPUTER CODE

The effect of cracking on the mechanical performance of the fuel cannot be exactly taken into account in the fuel modeling codes[8,10,7,3]. To do so it wound require:

1) knowledge of the precise location and size of every crack in the fuel; and

2) solution of the complete three-dimensional stress-strain problem without the aid of the major simplification afforded by the assumption of symmetry around the central axis.

Consequently the phenomena is modeled by assuming that crack occurs only on the principal planes.

The LIFE-II fuel-modeling computer code, at the end of each time step, computes whether fuel cracking would occur in any of the three principal directions. If the power has changed, the local thermal stresses are computed and superimposed on the average stresses for each fuel region. The cracking criteria is based on the fracture strength data for UO_2[10] which is represented by:

$$\sigma_f = 15000 + 3.7\ T_K$$

where

σ_f = fracture stress (psi)

T_K = temperature (°K)

When any of the principal stresses in a fuel region reach σ_f, the fuel cracks in that region. The stress components perpendicular to a crack vanish in the region, and the eleastic strain existing prior to crack is redistributed.

The effect of multiple cracking is treated in a manner that retains the cylindrical symmetry of the system in a macroscopic sense. Rather than treat a solid containing discrete fissures, an equivalent continuous solid body with modified elastic constants is used in the stress analysis.

Using a crack perpendicular to the axial direction for illustration, after cracking, the elastic behavior of the cracked fuel is described by:

$$\sigma_z = 0$$

$$\epsilon_r = (\sigma_r - \nu\sigma_\theta)/E$$

$$\epsilon_\theta = (\sigma_\theta - \nu\sigma_r)/E$$

$$\epsilon_z = -\nu(\sigma_r + \sigma_\theta)/E \qquad (6.1)$$

It is desired to represent the behavior of this cracked material as an isotropic material:

$$\epsilon_r = (\sigma_r^i - \nu^\mu \sigma_\theta^i - \nu^\mu \sigma_z^i)/E^\mu$$

$$\epsilon_\theta = (\sigma_\theta^i - \nu^\mu \sigma_r^i - \sigma^\mu \sigma_z^i)/E^\mu$$

$$\epsilon_z = (\sigma_f^i - \nu^\mu \sigma_r^i - \nu^\mu \sigma_\theta^i)/E^\mu \qquad (6.2)$$

where E^μ and ν^μ are the new elastic constants which are determined by the above equations:

$$E^\mu = \frac{2}{3} E \text{ and } \nu^\mu = \frac{1}{2} \nu$$

For a region with N cracks:

$$E^c = E\left(\frac{2}{3}\right)^N \text{ and } \nu^c = \nu\left(\frac{1}{2}\right)^N$$

When the fuel element operates without a power change during a time step, crack healing is allowed. Presently, cracks are assumed to heal whenever; a) the stresses in the region become compressive; b) the temperature exceeds 1400°C; and c) the time at steady state exceeds 1 hr. When cracks heal, the mechanical properties of the fuel are again restored to their usual (temperature dependent) values.

Element XO72-SOPC5 (mixed oxide pellets with 20 wt% Pu; cladding type 304H stainless steel, burnup 3.0 at %; initial diametral fuel cladding gap 14 mils) has been calculated four ways witn LIFE-II. The fuel operation history and the "equivalent" steady state average operation power history were run with and without fuel cracking. The results are summarized in Table VI.I, where the full history with fuel cracking was calibrated to agree with the experimental values[23].

Table VI.I shows that full power history runs allow faster gap closure than steady state runs. In steady state runs, fuel crack allows faster gap closure. These results are expected. It is particularly interesting, however, that when following the full power history, fuel-cladding contact is made earlier when fuel cracking is not allowed. This bacause without cracking higher stresses are supported in each of the fuel regions, and fuel ratchetting becomes more severe.

7 – CONCLUSION

The fuel pellet crack healing time is an important factor because the as-fabricated fracture strength is fully recovered after the healing. Three crack healing correlations[20,1,13] are plotted in Figure 7.1. The correlations[1,13] that include the stress acting on the crack surfaces in contact are represented by full and dashed lines. The figure shows that these two correlations yield quite similar results and 1 MN/m^2 is a good estimate of that stress.

The result of the experiment performed by Lawrence descibed in Section 5 showed an increase of 25% gap closure after 5 cycles of 20 h instiad of 1 cycle of 100 h. This increase is expected. But the

40% gap closure after one cycle during 100 h is not well-understood. Swelling is not supposed to occur after such a short period of time although the heat rate is quite high (25 KW/ft). The sudden large pellet diameter increase is also noticed in low power tests[16].

It is known that the effect of pellet cracking and healing on gap closure depends on the number of power cycles, the cycle period and the temperature profile inside the fuel. In Figure 5.1 the percent gap closure was plotted vs the number of efficient cycles at several different temperatures. The cycle period was not mentioned by the authors.

Experiments performed in recent years have been of great help for modeling the complex phenomena of fuel cracking. However, it is clear that there is a considerable need for improvement due to the importance of fuel gap closure. Further experiments should be performed and the effect of the several paramenters examined in detail.

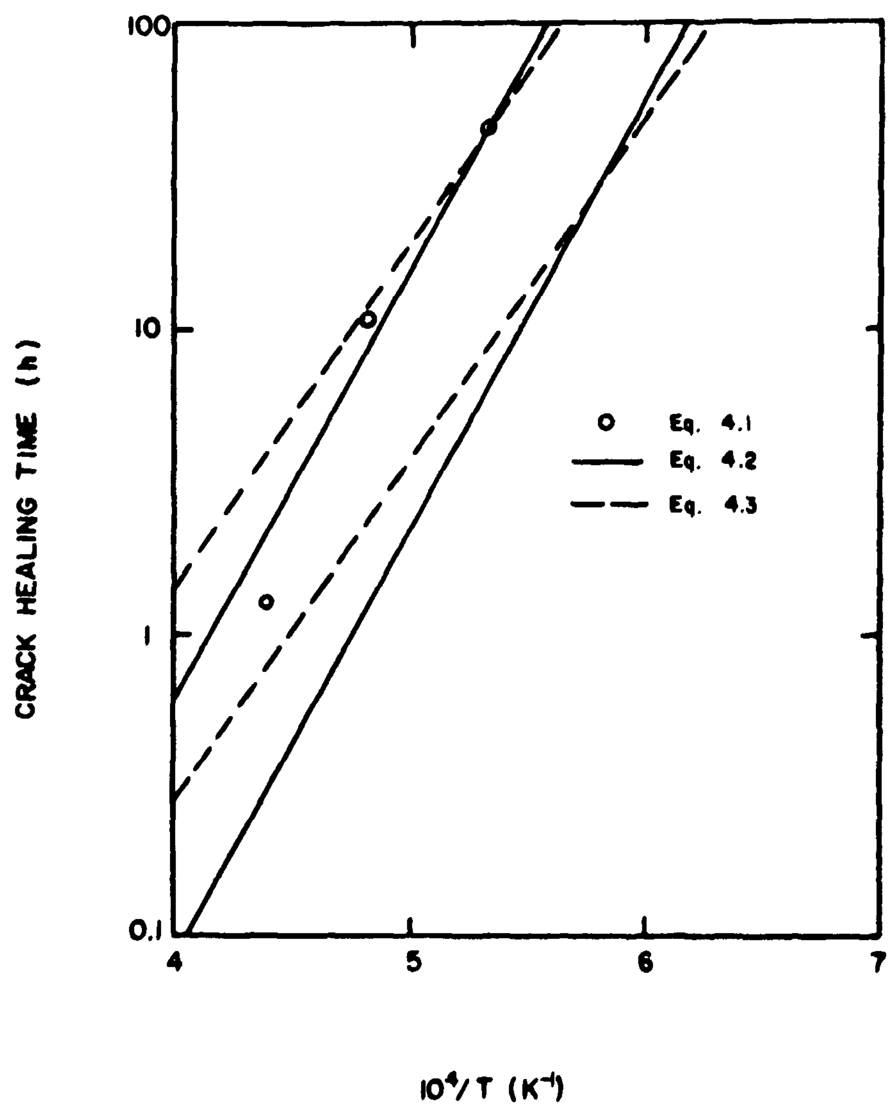

Figure 7.1 – Comparison of Crack Healing Models[1,2,22].

Table VI.1

LIFE-II Results for Fuel Element XO72 – SOPC5[10].

	Experimental values	Full history (274 days) with fuel cracking	Full history (274 days) without fuel cracking	Steady operating power (275 days) (8.1 KW/ft) with fuel cracking	Steady operating power (275 days) (8.1 KW/ft) without fuel vracking
1. Total fluence |NVT|	~$2.2.10^{22}$	$2.21.10^{22}$	$2.24.10^{22}$	$2.24.10^{22}$	$2.24.10^{22}$
2. Clad swelling strain |%|	0.13	0.14	0.14	0.16	0.16
3. Clad creep strain |%|	–	0.001	0.21	0.001	0.001
4. ΔD/final |%|	~0.17	0.17	0.37	0.18	0.19
5. Time of gap closure HR	gap closed	850	125	1620	~ 3200
6. Outer radius of columnar zone IN	~0.100	0.106	0.095	0.43	0.043
7. Fission gas realeased %	56.4	56.2	55.3	50.8	51.4

RESUMO

Na operação normal de um reator nuclear sabe-se que as pastilhas de combustível trincam radialmente. Quando a temperatura do combustível atinge níveis que levam as zonas centrais da pastilha à região plástica as rachaduras são parcialmente fechadas. A repetição dos fenômenos de abertura e fechamento das rachaduras resultam dos repetidos ciclos de potência, que o combustível é submetido. Isto tem um efeito considerável na reacomodação do combustível. O processo de reacomodação deve ser corretamente analisado pois tem efeito direto na vida útil do encamisamento.

~~Este trabalho descreve~~ os fenômenos de abertura e fechamento de rachaduras na operação de um reator e ~~também discute~~ os métodos de análise pertinentes,

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